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# SYSTEMS STUDY OF AIR POLLUTION FROM MUNICIPAL INCINERATION

A Report to

THE DIVISION OF PROCESS CONTROL ENGINEERING
NATIONAL AIR POLLUTION CONTROL ADMINISTRATION
U.S. DEPARTMENT OF HEALTH, EDUCATION AND WELFARE

UNDER CONTRACT CPA-22-69-23

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# I. INTRODUCTION

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# I. INTRODUCTION

## A. PURPOSE AND SCOPE

This study was undertaken by Arthur D. Little, Inc., under contract* to The National Air Pollution Control Administration (NAPCA) as another of many efforts being taken to control pollution of the air, specifically that caused by municipal incinerator systems. The overall purpose of the study was threefold:

1) To define and evaluate present and projected air pollution problems resulting from the incineration of municipal refuse;

2) To analyze all methods and techniques for reducing atmospheric emissions from incinerator systems from the viewpoint of both present and advanced technology and basic economy; and

3) To evaluate the study conclusions and recommend detailed research and development programs designed (a) to improve present incinerator control device systems, and (b) to develop new low air pollution processes for use in the thermal reduction and conversion of municipal solid waste.

Based on a multitude of existing data on this subject, complemented by extensive information garnered from the questionnaire survey (Vol. II, Appendix D) conducted as part of this study, methods to cope with the air pollution problems engendered by municipal waste incineration were analyzed and evaluated in the light of both present and future problems.

Our study resulted in recommendations (cited in Chapter III) which should prove of value to existing plant owners, municipalities evaluating various alternatives in contemporary incineration systems, and to the federal, state, and private organizations which are looking for the latest advances in incineration technology, especially from the viewpoint of air pollution control.

In general, this study was limited to incineration systems – present and planned – now operating in the United States, although technical contributions from Europe have been included to a lesser extent (Vol. II, Appendix E). The study was further limited to the solid waste associated with the home and commerce, thus effectively excluding industrial, agricultural, and bulky municipal waste, sewage sludge, and the like. Covering the latter would have made the report far too comprehensive for this initial study. Finally, the report was based on a compendium of existing data with no experiments being conducted to verify or qualify any of the conclusions drawn.

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*Contract No. CPA-22-69-23.

## B. BACKGROUND

Presently the total quantity of municipal solid waste generated in the United States is about 200 million tons per year. Some 90 percent of this waste is disposed of by landfill, with only 9 percent being incinerated. The nub of the problem is that waste requiring disposal is increasing at the rate of 7 million tons per year, while the area available for economic disposal by landfill is rapidly dwindling. An alternative, of course, is to incinerate an increased percentage of this material. Of course, the air pollution problem would grow proportionately unless new, more effective and efficient burning processes were to be adopted. However, incineration is an increasingly attractive solution, and it becomes still more attractive economically as land values and transportation costs continue to rise. The fact that incineration facilities can be located near population centers and require greatly reduced land areas in comparison to landfills enhances their attractiveness to urban planners. Thus – in spite of the air pollution problems (which are largely controllable as this report will point out) – incineration will continue as an important method of disposal in the decades ahead.

With this background in mind, the Arthur D. Little (ADL) study team proposed a comprehensive overview of the whole incineration industry and an evaluation of its findings with a view to diminishing air pollution. The major categories chosen for study, based on the Scope of Work outlined by NAPCA are discussed briefly in the following paragraphs.

### 1. Solid Waste Disposal and Incineration

Our study of the present and future quantities of solid waste collected for disposal in the urban areas of the United States [as characterized by the State Economic Areas (SEA's)] showed an approximate 80 million ton per year disposal problem in 1968. With population growth and migration and waste generation rates increasing normally in the future, the waste disposal burden projects to more than 270 million tons per year by the year 2000. The SEA's, although representing only about one-half of the U.S. population, were singled out for the analysis since they represent areas in which the highest concentrations of waste generation and the financial resources required to support incineration facilities are located.

Our study showed further that an incinerator capacity of some 90,000 tons per 24-hour day (TPD) was presently existing and active in the United States. However, a mathematical model, constructed specifically for this study, projected an increased active incinerator capacity of some 310,000 TPD total by the year 2000. The model reflected historical trends in incinerator construction as affected by per-capita waste generation and population growth, and was further augmented by consideration of decreasing land availability and the rapidly increasing population density projected for the future.

Presently, on an assumed plant use factor of 50%, incinerators are processing about 20% of the SEA-collected waste. By 2000, however, about 27% of this solid waste is expected to be processed by incineration.

### 2. Incinerator Air Pollution

For purposes of credibility, incinerator air pollution emission data were collected from a wide variety of sources and correlated, as nearly as possible, with refuse composition and incinerator design characteristics and operating parameters. Estimates of the potential pollution load, both uncontrolled (furnace emissions) and abated by air pollution control (APC) devices (stack emissions), were provided by combining the resulting emission factors with the present and future forecast of the incinerator inventory. Consideration was given to the effects of changing refuse composition. The estimates for the reference year (1968) and the projected year (2000) are summarized, by pollutant, in Table I-1.

**TABLE I-1**

**ESTIMATED INCINERATOR EMISSIONS**
**(thousands of tons per year)**

| | 1968 Emissions Estimate | | 2000 Emissions Estimate | |
|---|---|---|---|---|
| **Pollutant** | **Furnace** | **Stack** | **Furnace** | **Stack** |
| Mineral Particulate | 90 | 56 | 708 | 118 |
| Combustible Particulate | 38 | 32 | 131 | 49 |
| Carbon Monoxide | 280 | 280 | 829 | 829 |
| Subtotal (particulates) | 182 | 142 | 1064 | 391 |
| Hydrocarbons | 22 | 22 | 64 | 64 |
| Sulfur Dioxide | 32 | 32 | 161 | 160 |
| Nitrogen Oxides | 26 | 22 | 147 | 114 |
| Hydrogen Chloride | 8 | 6 | 219 | 147 |
| Volatile Metals (lead) | 0.3 | 0.3 | 0.055 | 0.025 |
| Polynuclear Hydrocarbons | 0.01 | 0.005 | 0.03 | 0.009 |
| Total | 496. | 450. | 2259. | 1481. |

In general, the public's increasing concern for air pollution abatement (Earth Day, 1970, for example) in the urban environment is reflected in the air pollution control patterns evident in the nation today. The interest in new incineration technology, particularly concepts based on pyrolysis, points to the potential for reversing the trend in total incinerator emissions, particularly mineral particulate and combustible pollutants.

### 3. Air Pollution Control for Incinerators

An evaluation of contemporary air pollution control (APC) systems was made by the ADL study team using theoretical analysis to supplement the limited data regarding APC effectiveness in the treatment of incinerator effluents. However, the evaluation, coupled with operating experience recorded both in the United States and Europe, showed clearly that the greater percentage of particulate emissions from incinerators could be adequately controlled by existing APC equipment. Its implementation is contingent upon the municipal decision-makers, since the technology for controlling the major particulate pollutant now easily permits it.

On the other hand, a sizable percentage of incinerator air pollutants cannot as yet be controlled by existing APC devices. Certain pollutants, such as very small particulates ($< 1\ \mu$), and a variety of combustible gases, such as hydrocarbons and carbon monoxide, fall into this category. Although exotic catalytic agents and unique absorbent systems can be postulated to control such pollutants, cost constraints point to combustion within the incinerator as more plausible. In fact, a burnout analysis of these pollutants indicated the residence time in contemporary incinerators, even under the worst of conditions, to be several orders of magnitude higher than calculated combustion times. High combustible pollutant emission thus points to inadequate mixing within the incinerator system where the combustible and the oxidant are prevented from mixing adequately. Because such mixing is evidently possible when other low-rank fossil fuels are used in industrial practice, substantial improvement in diminishing pollution of the air from incineration should ensue once this knowledge is properly exploited.

Calculations were also made based on various assumptions concerning the weighted average particulate removal efficiency of new APC systems. Estimates of total operating costs for these assumptions showed that shifting to a national average of 90% particulate removal efficiency for all new plants would approximately double the operating costs associated with the air pollution control systems above those of present systems. The impact on total cost of incineration, however, would approximate only 6%. Based on these projections, it appears that continued use of air pollution control systems in the particulate removal efficiency range characterized by those units installed during the past five years (only 52% removal) will lead to a fivefold increase in mineral particulate emissions by the year 2000. This trend may be moderated to a threefold increase or stopped entirely by the use of 70% and 90% average efficiency APC systems, respectively.

### 4. Technical-Economic Analysis

A technical-economic analysis of various aspects of incineration technology was undertaken by the ADL study team to (1) assist the existing incinerator plant owner in improving the air pollution performance of his plant; (2) offer background information to the municipality seeking a contemporary incineration system offering optimum performance; and (3) point out to various municipal, state, and federal agencies the opportunities available in new incineration technology to realize both satisfactory incineration and minimum air pollution – all within pertinent economic constraints.

To meet the first objective, a detailed analysis of contemporary incineration systems was made. Although minimum air pollution is an important and increasingly necessary constraint, the primary purpose of an incinerator is to dispose of solid waste at minimum cost and with maximum safety and reliability. With this in mind, incinerator performance was analyzed within the context of the several criteria of performance which any incineration system must meet. Thus, the interaction between decisions to modify design or operating practices to meet a specific need, such as air pollution, and other aspects of incinerator performance, such as efficiency and output, were carefully analyzed. The results were assembled into a general but comprehensive problem-solving manual (Vol. II, Appendix K).

The second portion of the analysis dealt with presenting alternatives in incinerator design based on existing technology, current incinerator practices and existing industrial processes and their inherent advantages and disadvantages, and ultimately their cost and performance. As in the first objective, only a general analysis was possible in view of the variation in local priorities precluding any one "best answer" in view of all the factors that had to be considered.

In general, the overall design characteristics of most incinerator systems can meet acceptable performance standards, including air pollution. However, in most cases studied, there was an unwillingness or inability of the municipality to reach for the ultimate in every aspect of incineration performance. In addition to design suitability, however, operating practices were found to vary from plant to plant with some organizations willing (or fortunate enough) to employ and support the type of operator who would effect top performance at all times, with others merely apathetic to the general qualification of its personnel and the state of repair of the equipment. Naturally in the latter case, the performance and efficiency of the plant was found to suffer, often resulting in substandard activity with attendant air pollution problems.

The third and last portion of the technical-economic study consisted of an evaluation of advanced concepts for the incineration of municipal solid waste. Presently three advanced incineration concepts, already proven in the chemical and metallurgical fields, show promise in incineration technology – (a) slagging incinerators wherein the residue is melted; (b) systems using a fluid-bed principle; and (3) systems using the pyrolysis principle. All represent improvements over contemporary incineration systems, but development of applied technologies for refuse feeding and handling, for example, will be necessary.

From a cost and performance viewpoint, no breakthrough appears imminent. However, the pyrolysis method of incineration appears very promising from an air pollution control viewpoint. Strictly speaking, pyrolysis is not a waste disposal concept, but rather a waste transformation concept. Although some volume reduction is accomplished, the primary effect is to transform a heterogeneous, unstorable, and difficult-to-handle fuel into a low Btu gas and liquid stream and a storable char material. These products are suitable for firing in conventional furnaces under more controlled conditions than is possible in conventional incinerators.

# II. STUDY APPROACH

# II. STUDY APPROACH

## A. REPORT DEVELOPMENT

Basically this report was formulated on a three-step approach to the various subjects studied. The first step consisted of the acquisition of data; the second, a standardization and analysis of that data; and the third, the development of conclusions, projections, and a number of evaluation tools which could be used by various sectors of the municipal and technical communities. The sections below touch briefly on the major phases of the study in light of this approach.

### 1. Collection and Standardization of Emission Data

This phase of the report was concentrated on the collection of emission data from municipal incinerator systems. Based on these data, so-called "emission factors," which provide useful measures of comparative air pollution performance, have been developed. Although these factors may have limited validity when applied to any particular plant, when related to system design or operating characteristics, they can be useful for area air pollution estimates and they suggest problem areas where research and development efforts may prove fruitful.

To develop a comprehensive set of emission factors for municipal incinerators, furnace emission data were obtained from consulting engineers, vendors, federal, state, and local pollution control agencies, and other sources. The resulting compendium of information established certain trends which permitted the association of discrete furnace emissions with certain basic incinerator types and operating practices. The data also revealed general influences of refuse composition on the emission factors. Although somewhat speculative, the influence coefficients may prove useful in predicting the impact of changing refuse composition on air pollution emissions.

### 2. Incinerator Inventory

Based on detailed reviews of the literature and solicitation of data from a variety of sources, an incinerator inventory was assembled, identifying most of the incinerator systems now operating in the United States. Using data and an analysis of factors potentially important in encouraging new incinerator construction, we constructed a mathematical model to forecast incinerator construction trends into the future. Combining this forecast with projections of changing refuse composition and the emission factors, we made forecasts on air pollution emissions from municipal incineration through the year 2000.

### 3. Evaluation of Current Technology

Pertinent data on the design and operating characteristics and economics of contemporary incinerator plants were compiled from an extensive review of the existing literature, use of a questionnaire, and solicitation of state-of-the-art information from various members of the incinerator community. From these data, profiles of the technological and economic features of various incineration concepts were constructed to pinpoint the problem areas affecting incinerator performance.

### 4. Advanced Concepts

The most recent public information on advanced concepts now under development by various public and private agencies throughout the United States were also collected. Although such data are necessarily limited in scope and often untested in full scale operation, they nonetheless support a preliminary evaluation of the advantages, disadvantages, and potential economics of these advanced systems.

### 5. Applicability of Air Pollution Control Systems

Ultimately the selection of a particular type of APC device becomes a compromise between initial capital investment, annual operating cost, and efficiency collection. The study team's approach to an evaluation of APC devices for incinerators covered the anticipated performance and cost of conventional APC equipment, the types of equipment presently available and their predicted performance in handling waste matter, and their cost. Initially the ADL team looked at the performance data available on APC systems in general, focussing on their particulate removal efficiency and operational problems. Because of the limited data available, however, the team performed a theoretical analysis to arrive at a better estimate of the overall efficiency of the APC devices. Then, combining the theoretical data with the actual data, they were able to produce an optimum estimate of APC performance. An overall evaluation of APC systems was then made by combining the performance estimates with the operational and cost factors involved in the APC systems.

### 6. Research Plans

The above analysis of the existing art and new concepts now under development identified areas where more knowledge was necessary for future projections and planning. The research needs thus defined formed the basis for two alternative research and development programs (Chapter VIII). These programs were based on the expenditure of $5 million and $16 million, respectively.

## B. REPORT CONTENTS

The report covering this study is being presented in three separate volumes. Volume I contains the formal part of the report and focusses on the overall solid-waste and incineration air pollution problem (Chapters IV and VI); an exploration of the causes and cures of incinerator air pollution (Chapter V); the technical and economic ramifications of alternatives in incinerator design (Chapter VII); and research programs designed to reduce the air pollution problems associated with municipal incineration (Chapter VIII).

Volume II contains a series of appendices representing a compendium of information used to support statements and conclusions presented in Volume I and also dealing with specific subsystem or other aspects of the incineration process applicable to a variety of incineration concepts.

Volume III is a comprehensive bibliography encompassing all major aspects of municipal incinerator air pollution and represents much of the fundamental information upon which the report was based. The contents of Volumes I and II are described in more detail in the following subsections.

### 1. Contents of Volume I

Chapter I opens with a declaration of the purpose and scope of the overall report, and presents pertinent summary background information on the study effort, including data on solid-waste disposal and incineration, incinerator air pollution, air pollution controls for incinerators, and a technical-economic analysis.

Chapter II outlines the three-step study approach, commenting on the collection and standardization of emission data, an incinerator inventory, an evaluation of current technology, advanced concepts, applicability of air pollution control, and finally research plans. It concludes with a brief outline of the overall report contents, including a brief summary of the appendices.

Chapter III summarizes the conclusions and recommendations made by the ADL study team in some depth. The overall perspective of the study is presented with pertinent suggestions for reducing air pollution aimed at municipal, state, federal, and private incinerator agencies and organizations.

Chapter IV comments on the nature of the solid-waste problem, citing the growing quantity of municipal solid waste and the changing nature of refuse as two factors which will have an immediate bearing on the incinerator air pollution problem and future incinerator design. In view of these factors, the chapter discusses the present national solid waste load and the nature of refuse. With these values as a base, techniques are described for predicting the solid waste loads and the physical and chemical nature of refuse through the year 2000.

Chapter V discusses the nature and causes of incinerator air pollution. The chapter treats the three classes of pollutants associated with incinerators – particulate, combustible, and noncombustible – and the mechanisms by which these pollutants arise in the course of incineration.

Chapter VI ties in with Chapter IV in which the substantial growth in the quantity of collected solid waste was illustrated, and projected for the future. To provide an estimate of this increase, an analysis was made to identify the factors affecting the magnitude of the incineration air pollution problem through the year 2000. After characterizing the air pollution potential from a variety of incinerator types, and defining the emission factors for each furnace type, a mathematical projection model was prepared to predict future incinerator capacity.

Chapter VII presents a comprehensive technical-economic analysis of the air pollution aspects of municipal incineration. It covers the technical and economic aspects of air pollution control devices for incinerators, modifications to existing plants, an analysis of incineration concepts based on existing technology, and incineration concepts based on advanced technology.

Chapter VIII presents research and development programs needed to stem the tide of the incinerator air pollution threat of the future. The chapter comments on the magnitude and nature of the solid-waste problem as it affects air pollution from incineration, as well as the magnitude and nature of air pollution from incineration, the causes of incinerator air pollution, and some advanced concepts, with a detailed listing of R&D programs respectively related to the individual problems. The chapter concludes with two suggested research programs one for $5 million, the other for $16 million.

### 2. Contents of Volume II

Volume II consists of 11 appendices providing a wealth of background information on various aspects of the study effort. A list of the appendices and a brief description of each are presented below:

*Appendix A – Size Reduction Costs*

A number of incineration concepts, especially those involving fluid bed or suspension burning, are based on refuse size reduction. This appendix includes an analysis of data recently collected by the Battelle Memorial Institute under contract with the Bureau of Solid Waste Management, and presents cost curves which permit estimates of capital and operating costs for this operation.

*Appendix B – Flue Gas Conditioning*

This appendix covers flue gas conditioning, defined as the cooling of flue gas after it has left the combustion zone to permit discharge to mechanical equipment, such as dry air pollution control (APC) devices and fans or a stack. The appendix discusses technical and economic aspects of both wet and dry methods used to cool incinerator flue gas streams.

*Appendix C – Refuse Stoichiometry*

This appendix is concerned with the relative flows of the principal material and energy streams associated with refuse burning systems, and serves to explain the processing system which receives matter and energy in one form (refuse) and discharges it, appropriately transformed (burned), in one or more other forms (flue gas, ash, sensible and latent heat, etc.).

*Appendix D – Incinerator Questionnaire*

This appendix consists of the questionnaire sent to representative segments of the incineration industry to provide information for analysis on the various aspects of the industry. In addition to presenting questions posed, the appendix includes a copy of a representative diagram data sheet.

*Appendix E – Operating Experience on European Electrostatic Precipitators*

Because of the unique chemical nature of incinerator flue gases and particulate with respect to corrosion and abrasiveness, information on operating problems was solicited from plant superintendents of five European incinerators. Their comments are summarized in this appendix.

*Appendix F – By-Product Recovery*

This appendix presents various aspects of by-product recovery associated with incineration. In the main, it covers the economics and methods associated with the recovery of paper, metal, and heat.

*Appendix G – Refuse Composition and Projection Data*

This appendix presents data on the composition of municipal refuse taken from four locations in the United States supplementing those presented in Chapter IV. It also presents the growth rate projections for each refuse category used in calculating the composition and quantity of solid waste in the future.

*Appendix H – The Incineration Process*

This appendix summarizes the equipment options, general combustion principles, and criteria of performance applicable to contemporary incineration practices. For the benefit of readers unfamiliar with the details of incinerator practice and principles, these subjects are presented in summary form.

*Appendix I – Present Municipal Incinerators in the United States*

This appendix indicates current design trends and operating practices in existing incinerators in the United States, including a description of the present incinerator inventory. It also includes the results of a questionnaire solicitation which sought both design and operating data from active incinerator plants.

*Appendix J – Incinerator Emission Data*

This appendix presents tables of emission data used in Chapter V to establish relationships between air pollution, on the one hand, and the complex function of plant design, operating practices, and refuse composition on the other.

*Appendix K – Causes and Cures for Incinerator Deficiencies Affecting Criteria of Performance*

This appendix presents a detailed evaluation of incinerator problems and specific actions for their solution. The interaction of these specific actions with other aspects of incinerator performance is identified by use of a unique "parameter number" concept.

# III. SUMMARY

## III. SUMMARY

This chapter presents an overall summary of the conclusions and recommendations of the ADL study effort. In addition, the chapter summarizes the highlights of each of the major chapters, presenting, where appropriate, data in tables and illustrations which had a significant bearing upon the conclusions and recommendations reached. Thus the reader may readily gain an overall perspective of the current state of technology in incinerator design and operation as well as a general overview of the needs and resources of the incinerator community.

### A. CONCLUSIONS

#### 1. The State of the Art in Incinerator Technology

In response to the need for larger, more efficient solid waste disposal facilities, incineration technology is developing rapidly. Conservatism, however, is inherent in the municipality, reflecting, in part, the limited interest and financial resources of the cities in conducting exploratory research, and, perhaps, the political penalties of failure. Communications are improving, however, between the municipalities, the consulting engineers often involved in incinerator design, research firms, contractors, vendors, and the academic community. Still, the realization of improved technology in new plant construction is slow.

Although a number of problem areas still exist in contemporary incineration systems, it is within the state-of-the-art to design and build efficient and reliable incinerator systems producing a minimum of air pollution. Interaction of incinerator designers with individuals and firms skilled in the combustion of comparable fuel materials in industrial applications (bagasse, wood, bark, etc.) can result in the infusion of needed technology to assure adequate burnout of combustible pollutants.

Substantial advancements in the incinerator art will most likely arise from the investment of federal and state efforts and research funds. As indicated above, one cannot look to the municipalities for this leadership. Private organizations, although showing increasing interest in municipal solid waste disposal, are cautious as a result of the large investments required for successful penetration and participation in this market area. Federal assistance in the demonstration of existing technology from the power, chemical and metallurgical industries can speed the technology transfer needed by the incineration community. Also, new concepts can be more rapidly brought into the practiced art as a result of federal support. Such technologic contributions can make substantial improvements in the national incinerator air pollution forecasts.

### 2. Incinerator Air Pollution Potential

The increasing quantity of solid waste will demand the construction of new incinerator capacity. Although a number of municipalities have avoided commitment on new capacity in recent years, this trend will not continue. As a result, the potential air pollution from incineration will increase substantially over the next several years. Because of the typical location of incinerators in the central city, this pollutant load will be concentrated in our urban centers.

Contemporary air pollution control systems can produce acceptable effluent quality, although not without cost. A substantial reduction in future emissions from this source can be effected by communities assuming responsibility for air quality. Air pollution from existing plants can be reduced by improved operating procedures, modifications to the physical plant, or by the installation of effective air pollution control devices. The technology exists; all that is needed is motivation and commitment.

### 3. Data Summaries and Specific Conclusions

#### a. The Solid Waste Problem

The increasing quantity of collected municipal solid waste, coupled with the changing nature of refuse composition in general – composition, heating value, ash content, and the like – point to the need for expanded incineration facilities for the future and new plant design to allay the attendant air pollution problem bound to ensue.

Because the design and operating parameters of future incineration facilities will be significantly influenced by the changing physical and chemical nature of the refuse, not to mention its ever-increasing quantity, the present national solid waste load and the composition of the refuse were estimated. With these values serving as a base, projection techniques were developed to predict solid waste loads and the physical-chemical composition through the year 2000. Table III-1 presents a statistical analysis of the national annual average composition of municipal refuse in 1968 (excluding yard wastes and miscellaneous categories).

*(1) Municipal Waste Composition.* These data were computed from 23 sources and modified to reflect an average composition of municipal waste. Chapter IV-B provides more details on the survey and method of analysis. The averages and confidence range can only be considered estimates of the composition of average national refuse because of the limited quantity of data available. Also, some variations can be expected, reflecting localized mixes of commercial and domestic waste sources, industrial wastes, and so forth.

## TABLE III–1

### ESTIMATE OF THE NATIONAL ANNUAL AVERAGE COMPOSITION OF MUNICIPAL REFUSE EXCLUDING YARD WASTES AND MISCELLANEOUS CATEGORIES

(as-fired basis)

| (1) Component | (2) Data* Samples Utilized | (3) Mean Weight Percent | (4) % Mean (100% basis) | (5) Estimated Standard Deviation S(X) | (6) 95% Confidence Limits | (7) 95% Confidence Range |
|---|---|---|---|---|---|---|
| Glass | 23 | 9.7 | 9.9 | 4.37 | 1.89 | 8.0-11.8 |
| Metal | 23 | 10.0 | 10.2 | 2.18 | .93 | 9.3-11.1 |
| Paper | 23 | 50.3 | 51.6 | 11.67 | 5.04 | 46.6-56.6 |
| Plastics | 9 | 1.4 | 1.4 | .96 | .74 | 0.7-2.1 |
| Leather & Rubber | 9 | 1.9 | 1.9 | 1.62 | 1.25 | 0.7-3.2 |
| Textiles | 17 | 2.6 | 2.7 | 1.80 | .93 | 1.8-3.6 |
| Wood | 22 | 2.9 | 3.0 | 2.39 | 1.06 | 1.9-4.1 |
| Food Wastes | 23 | 18.8 | 19.3 | 10.95 | 4.73 | 14.6-24.0 |
| | | 97.6 | | | | |

*Several data sets were not presented in a form suitable for extracting the weight fractions of all of the above refuse components.

The refuse compositions were considered on an "as discarded" versus an "as fired" basis, since the relative distribution of waste categories in the refuse as they were discarded is an important consideration in establishing and projecting the quantities of individual refuse categories.* The moisture content values from Table IV-7 were used to adjust the "as-fired" values to an "as-discarded" basis for refuse compositions in projecting refuse compositions through the year 2000.

The reference composition in Table III-1 does not include yard-waste (twigs, grass, brush) or miscellaneous matter (rocks, demolition waste, ashes, etc.) as the amounts of these categories were found to vary widely from place-to-place and from season-to-season. An average value of 1.7% miscellaneous in refuse (on a yard-waste free basis) was used in the projections. Yard waste contributions to the annual average domestic/commercial refuse composition were estimated on a state-by-state basis using the number of frost-free days per year as a yardstick of the length of the growing season and thus the average quantity of yard waste in refuse.

*(2) Refuse Projections.* The analysis of waste composition described at length in Chapter IV provided a firm reference point from which the changing nature and relative quantity of solid waste could be projected into the future.

To project the per-capita waste loads and refuse compositions for each state, national indicators of quantity and growth rate for each of the 10 major categories comprising municipal solid waste were selected. Appendix G presents the indicator projections in detail. Each indicator represents a projection of the national growth rate of the subject categories beyond its present contribution to solid waste composition. The projected national annual growth rate of each of the 10 major refuse components, based on the indicator projections, is presented in Table III-2.

Refuse generation projection for the three U.S. regions (Table IV-13) and other computed refuse properties and statistics (Table IV-14) are also presented in the chapter. The anticipated changes in the nature of the refuse over the next 30 years are particularly significant. Over the same time span, study data point to a more than 70% increase in the per capita refuse generation rate over the current level which, when compounded by the effect of increasing population, will increase by a factor of 2.65 the quantity of generated solid waste. Thus, a community with a stable population level may well experience a refuse disposal requirement increase of 70% and an area growing in population at the national average rate will require an incineration capacity over 2.5 times that in 1968 by the year 2000.

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*These data estimates are presented in detail in Table IV-7.

## TABLE III–2

## EQUATIONS FOR PROJECTING THE QUANTITY AND COMPOSITION OF DOMESTIC AND COMMERCIAL REFUSE

Let:

$L_j$ = The total collected refuse quantity within a specific state or region in the $j^{th}$ year.

$L_{ij}$ = The quantity of the $i^{th}$ refuse component generated within a specific state or region in the $j^{th}$ year.

$\Gamma_j$ = The per-capita total quantity of refuse generated within a specific state or region in the $j^{th}$ year.

$\Gamma_{ij}$ = The per-capita quantity of the $i^{th}$ component of refuse generated within a specific state or region in the $j^{th}$ year.

$P_j$ = The population of a specific state or region in the $j^{th}$ year.

$X_{ij}$ = The weight fraction of the $i^{th}$ component of refuse generated within a specific state or region in the $j^{th}$ year.

$\Gamma'_{ij}$ = The national per-capita refuse quantity of the $i^{th}$ component generated in the $j^{th}$ year.

A. Local Refuse Load ($L_j$)

$$L_j = F_j P_j \Gamma_j \tag{1}$$

$$\cong F_j P_j \sum_{i=1}^{N} \Gamma_{i\beta} \frac{\Gamma'_{ij}}{\Gamma'_{i\beta}} \tag{2}$$

$$= F_j P_j \sum_{i=1}^{N} \Gamma_\beta X_{i\beta} \frac{\Gamma'_{ij}}{\Gamma'_{i\beta}} \tag{3}$$

$$= F_j P_j \Gamma_\beta \sum_{i=1}^{N} X_{i\beta} \frac{1}{\Gamma_{i\beta'}} \Gamma'_{i\beta} \frac{(1+g'_i)^{(j-1968)}}{(1+g'_{pop})^{(j-1968)}} \tag{4}$$

$$L_j = F_j P_j \Gamma_\beta \sum_{i=1}^{10} X_{i\beta} \frac{(1+g'_i)^{(j-1968)}}{(1+g'_{pop})^{(j-1968)}} \tag{5}$$

B. Local Refuse Composition ($X_{ij}$)

$$X_{ij} = \frac{L_{ij}}{L_j} \tag{6}$$

### TABLE III–2 (Continued)

$g'_{pop}$ = The annual growth rate of the national population*

$g'_i$ = The annual growth rate of the national indicator for the $i^{th}$ refuse component.

$F_j$ = The fraction of total solid waste generated in the $j^{th}$ year which is collected for disposal.

$$\cong \frac{L_{i\beta}\,(1 + g'_i)^{(j-1968)}}{\sum_{i=1}^{N} L_{i\beta}\,(1 + g'_i)^{(j-1968)}} \qquad (7)$$

$$= \frac{L_\beta X_{i\beta}\,(1 + g'_i)^{(j-1968)}}{L_\beta\, \Sigma X_{i\beta}\,(1 + g'_i)^{(j-1968)}} \qquad (8)$$

$$X_{ij} = \frac{X_{i\beta}\,(1 + g'_i)^{(j-1968)}}{\sum_{i=1}^{N} X_{i\beta}\,(1 + g'_i)^{(j-1968)}} \qquad (9)$$

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Where the Greek letter $\beta$ appears in subscripts, the variable subscripted refers to the base year, 1968.

Where the prime appears ('), this signifies a national average value.

*Schedule C – U.S. Bureau of the Census

The per capita refuse generation and collection figures for the U.S. by state are presented in Table III-3. The urban areas are of primary interest as regards incineration, as high-population density provides the incentives and financial resources necessary for incinerator construction.

Using a mathematical model (described below), the total quantity of municipal refuse collected in the urban areas of the United States (as characterized by the state economic areas) was estimated. The results are shown in Figure III-1. The almost fourfold increase in collected solid waste shown in these results suggests the importance of improving and expanding solid-waste management practices.

### b. The Nature and Causes of Incinerator Air Pollution

Knowledge of the nature and causes of air pollution from incinerators is fundamental to selecting, designing, and operating new and existing plants. The pollutants associated with incinerators fall into three categories: particulate (both mineral and combustible), combustible gases (carbon monoxide, hydrocarbons, and polynuclear hydrocarbons), and noncombustible gases (nitrogen oxides, sulfur oxides, and hydrogen chloride).

To characterize the various emissions and develop emission factors characteristic of municipal incinerators, reference was made to existing data (Appendix J). The tables presented in Chapter V break out the specific emission contents, percentages, and factors as they contribute to the overall air pollution problem.

*(1) Particulate Emissions.* Excessive particulate emission has been the source of the majority of complaints made against incinerators as a consequence of either the high rate of dust deposition in the vicinity of a unit or the production of aesthetically displeasing plumes. The amount, composition, and size distribution of the emitted particulate depend on undergrate air velocity, refuse ash content, burning rate, furnace temperature, grate agitation (continuous feed), or batch size, method and frequency of feeding and stoking (batch units) and combustion chamber design. The large number of important variables affecting emission rate leads to a dispersion of the data as shown in Figure III-2.

The emission factors (the emission rate, either stack or furnace, normalized to some standard) vary with the design and operational characteristics of the individual incinerators. Thus, the main controllable factors determining particulate emissions – (a) mechanical entrainment of particles from the refuse bed by the undergrate air flow, and (b) the cracking of pyrolysis gases to form soot – must be considered when diminution of these air pollutants become desirable.

## TABLE III-3

## U.S. REFUSE GENERATION AND COLLECTION

| | 1968 Per Capita Refuse Rate (pounds/day) | | | |
|---|---|---|---|---|
| | Generated*** | Collected | | |
| State | Urban | Urban | Urban Percent* | Rural |
| Alabama | 6.42 | 2.32 | 36 | 2.64 |
| Arizona | 6.51 | ** | 95 | – |
| Arkansas | 6.20 | 2.94 | 47 | 4.06 |
| California | 6.80 | 7.58 | 95 | 7.62 |
| Colorado | 5.81 | 7.41 | 95 | 8.09 |
| Connecticut | 5.89 | 6.45 | 95 | 7.30 |
| Delaware | 5.94 | 7.85** | 95 | 0.85 |
| Florida | 6.80 | 3.91 | 58 | 3.41 |
| Georgia | 6.20 | 2.90 | 47 | 2.61 |
| Idaho | 5.84 | 3.53 | 60 | 0.31 |
| Illinois | 5.95 | – | 69 | – |
| Indiana | 5.95 | 3.44 | 58 | 2.56 |
| Iowa | 5.90 | 6.35** | 95 | 0.98 |
| Kansas | 6.03 | 4.17 | 69 | 1.57 |
| Kentucky | 6.08 | 3.84 | 63 | 1.22 |
| Louisiana | 6.44 | 4.34 | 67 | 2.36 |
| Maine | 5.83 | – | 69 | – |
| Maryland and D.C. | 6.15 | 4.47 | 73 | 3.08 |
| Massachusetts | 5.94 | – | 69 | – |
| Michigan | 5.89 | 2.66 | 45 | 3.64 |
| Minnesota | 5.82 | 2.78 | 48 | – |
| Mississippi | 6.22 | 3.03 | 49 | 2.98 |
| Missouri | 6.08 | 4.68 | 77 | 2.20 |
| Montana | 5.67 | 9.08** | 95 | 1.62 |
| Nebraska | 5.92 | – | 69 | – |
| Nevada | 5.70 | 5.58 | 95 | – |
| New Hampshire | 5.70 | – | 69 | – |
| New Jersey | 6.03 | 6.02 | 95 | 3.37 |
| New Mexico | 5.97 | 2.47 | 41 | 0.61 |
| New York | 6.08 | 3.32 | 55 | 4.40 |
| North Carolina | 6.18 | 5.30 | 86 | – |
| North Dakota | 5.67 | 4.42 | 78 | 5.29 |
| Ohio | 5.96 | 3.61 | 61 | 3.65 |
| Oklahoma | 6.10 | 3.96 | 65 | 1.87 |
| Oregon | 6.34 | 3.05 | 48 | – |
| Pennsylvania | 6.14 | 4.28 | 70 | 4.26 |
| Rhode Island | 5.97 | 1.66 | 69 | 3.10 |
| South Carolina | 6.24 | 5.90 | 95 | 2.79 |
| South Dakota | 5.74 | – | 69 | – |
| Tennessee | 6.17 | 2.62 | 42 | 1.42 |

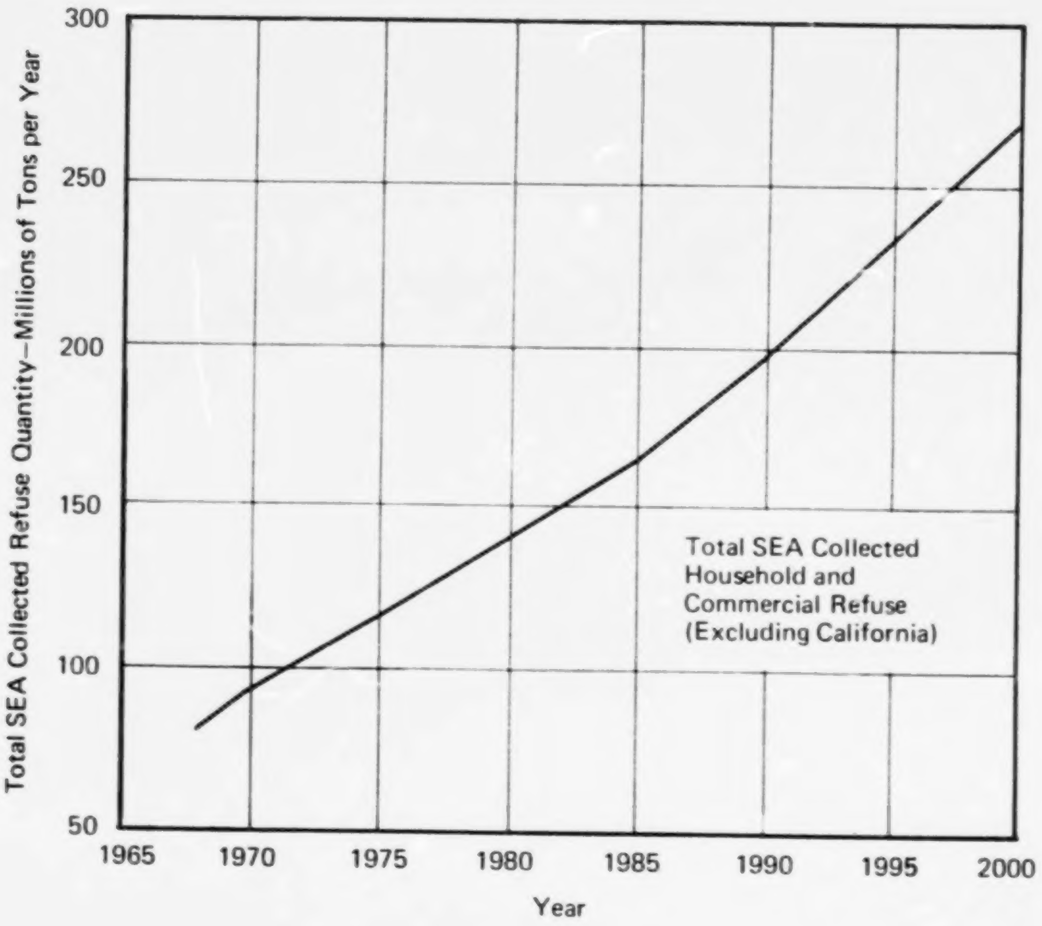


**FIGURE III–1** PROJECTED COLLECTED REFUSE QUANTITY

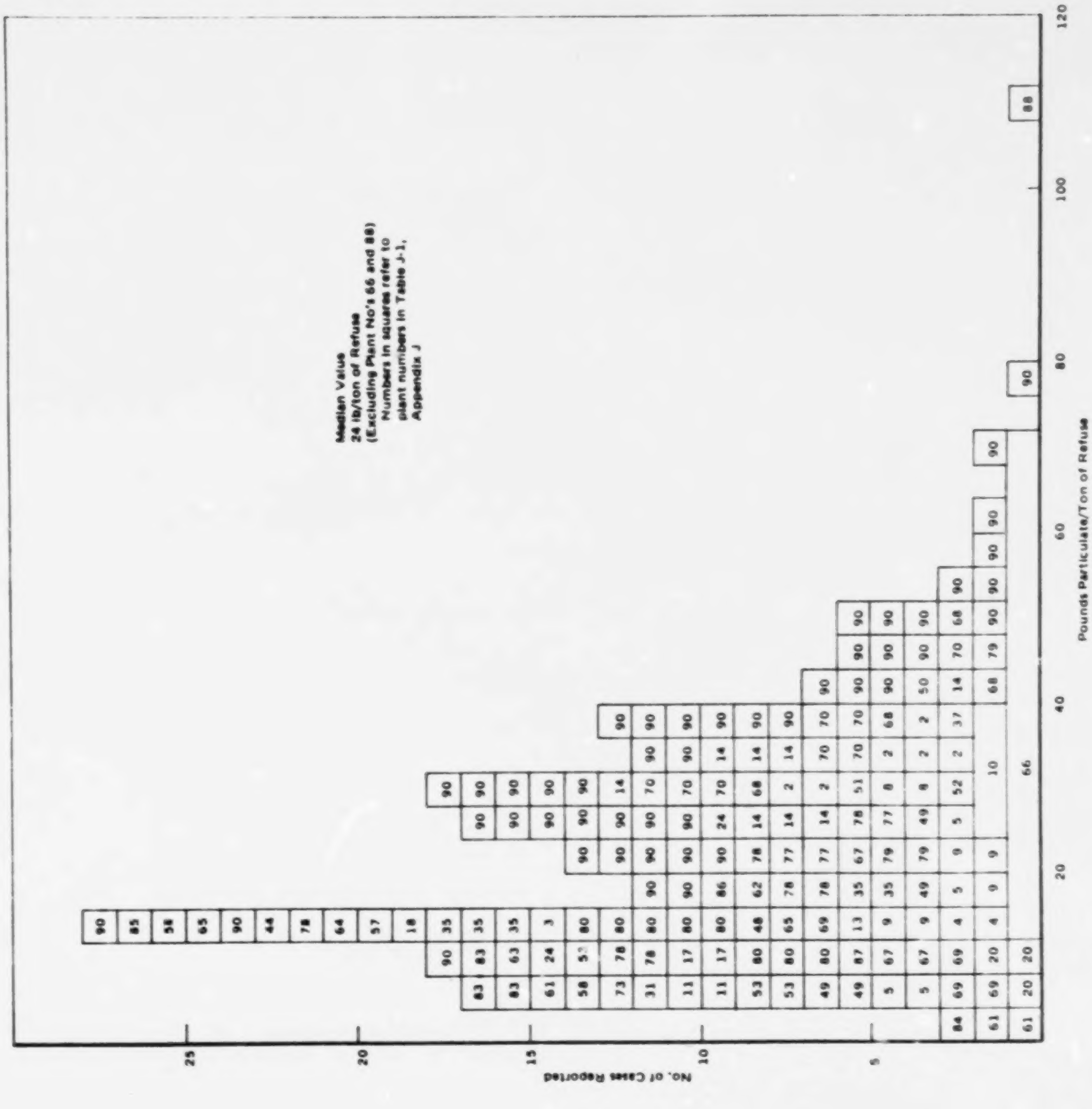


FIGURE III–2 HISTOGRAM OF PARTICULATE FURNACE EMISSION RATES FOR MUNICIPAL INCINERATORS
(Capacity>50 Ton/Day)

Mineral particulate, here defined as the incombustible fraction of fly ash, is composed mainly of mineral matter in waste that is entrained by the combustion air or combustion products. Oxidation of metals and the subsequent volatilization or entrainment of the oxides also contributes to the mineral particulates but, for mixed wastes, this usually contributes only a small fraction of the total particulate loading.

From consideration of the velocities that will entrain particles of different equivalent spherical diameters, it is estimated that the range of undergrate velocities usually encountered in incinerators will entrain particles with equivalent spherical diameters smaller than 70 to 400$\mu$ from the grate. Wide variations in emission of mineral particulate can, therefore, be expected, depending on the amount and size distribution of the ashed residue of the waste and on undergrate velocity. Estimates of the fraction of the fine ash content (i.e., excluding the metal and glass residues) of waste that is entrained off the grate may be obtained from consideration of data on three widely different grate stokers: a German municipal incinerator, a Public Health Service test incinerator operated on synthetic refuse, and an asphalt-saturated felt roofing and coal-fired stokers. Despite the very wide variation in incinerator type and material burned (the ash content varied from 2.5 to 50%), the fraction of the ash carried over for these units was in the range 10 to 20%, except for some runs made by the PHS with practically no underfire air.

The dependence of particulate emission on the ash content of refuse is thus particularly significant. The PHS and others have verified the particulate-ash content relationship in a number of tests (Chapter V, References 15 and 29). The results summarized in Table III-4 and Figure III-3 (the references in the figure may be found in Chapter V) show that low underfire air rates lessen the percentage of fly ash carryover. When more than 20% of the air requirements are supplied under the grate, the rate of emission of mineral particulate appears proportional to the 0.55 power of the air velocity. In this range, a two-fold reduction in air velocity will produce an approximately 30% reduction in emission rate. These test findings also indicate that refuse fine ash content is a major factor in determining emission rates.

Entrainment of mineral particulate, however, cannot be eliminated completely by reducing underfire air since the buoyancy of the combustion gases will induce an air flow that will produce a minimum particulate emission. From dimensional analysis, it can be shown that for a buoyancy driven flow the velocity V of the induced air flow is proportional to $\sqrt{L\Delta\rho/\rho g}$, where L is a characteristic length of the combustion chamber, $\Delta\rho$ is the difference in density between the colder entrained gases and the hot combustion products, $\rho$ is the mean density of the combustion products, and g is the gravitational acceleration. Entrainment of particulate by buoyancy driven flows will, therefore, increase with furnace size and flame temperature.

## TABLE III–4

### EFFECT OF ASH CONTENT ON EMISSION RATES[15]

| Refuse Ash Content (%) | Underfire Air % of Total | Emission Rate lb/ton | % Refuse Ash Emitted |
|---|---|---|---|
| 2.0 | 15 | 1.14 – 4.37 | 2.74 – 11 |
| 2.0 | 60 | 3.10 – 8.90 | 7.75 – 22 |
| 7.5 | 15 | 1.47 – 3.72 | 1.0 – 2.5 |
| 7.5 | 60 | 13.2 – 31.6 | 8.8 – 21 |

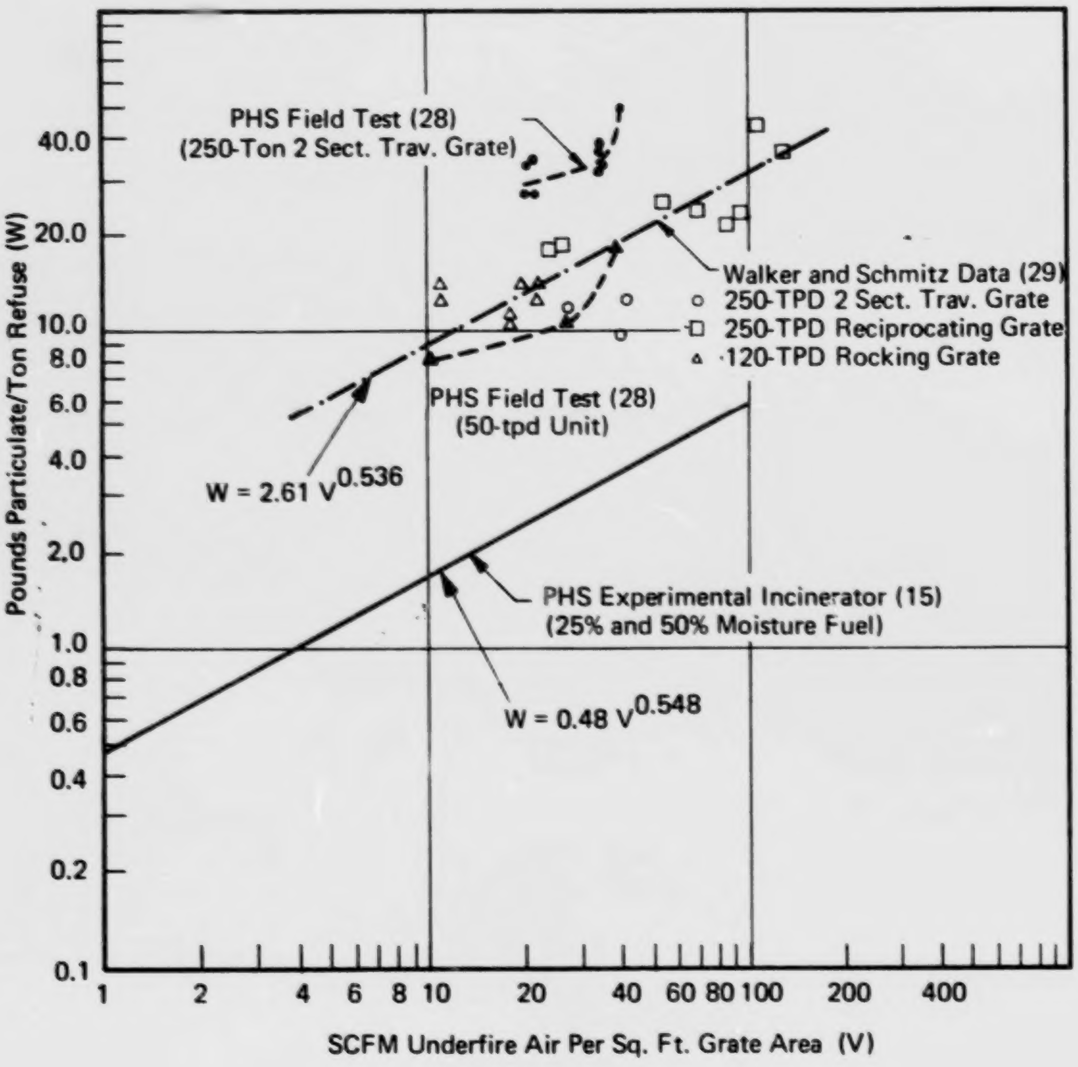


FIGURE III–3 EFFECT OF UNDERFIRE AIR RATE ON FURNACE EMISSION

An additional factor that enhances particulate emission is agitation (stoking) of the burning waste, but the magnitude of this factor has not been quantitatively established.

Combustible particulate consists of char (blackbirds) entrained from the grate, soot (black smoke) produced by the thermal cracking of pyrolysis products before these have been mixed with sufficient oxygen to complete their combustion, and an aerosol (white smoke) produced by the quenching of pyrolysis products before they have reacted. All three are highly visible and have a nuisance value in excess of their contribution to the total particulate emission rate.

Char formed from paper or sheets of other carbonizable material has a high surface-to-volume ratio and is, therefore, entrained at relatively low velocities in amounts that depend on the make-up and degree of agitation of the refuse bed. Inert material in the bed has a beneficial effect of keeping elements of char from being entrained. No quantitative estimate of the emission rate of charred waste components is available, but it is believed to be a small fraction of the total particulate emission.

The second source of combustible material – soot – is usually the most significant one. Soot particles, once formed, are relatively difficult to burn, and as a consequence of their characteristically small dimensions, are difficult to collect. The best form of control of black smoke is, therefore, the prevention of soot formation. This can be achieved by the rapid mixing of the pyrolysis gases with sufficient air to complete their combustion since it has been shown that with perfect mixing little soot is formed even under fuel-rich conditions.

The mechanism of soot formation is so complex, however, that the amounts of combustible particulate that leave a furnace chamber cannot be reliably estimated. The amounts of soot formed are a measure of the poor mixing conditions in a chamber and are expected to be greatest when a furnace is overcharged or when a waste having a high fraction of volatile carbon (total minus fixed carbon) is burned. Under normal operating conditions, the average combustible fraction of the particulates leaving combustion chambers of municipal incinerators is found to be about 15 percent. Because soot forms as submicron particles, however, it is difficult to collect and the fraction of combustible in the particulates leaving air pollution control devices can be considerably higher.

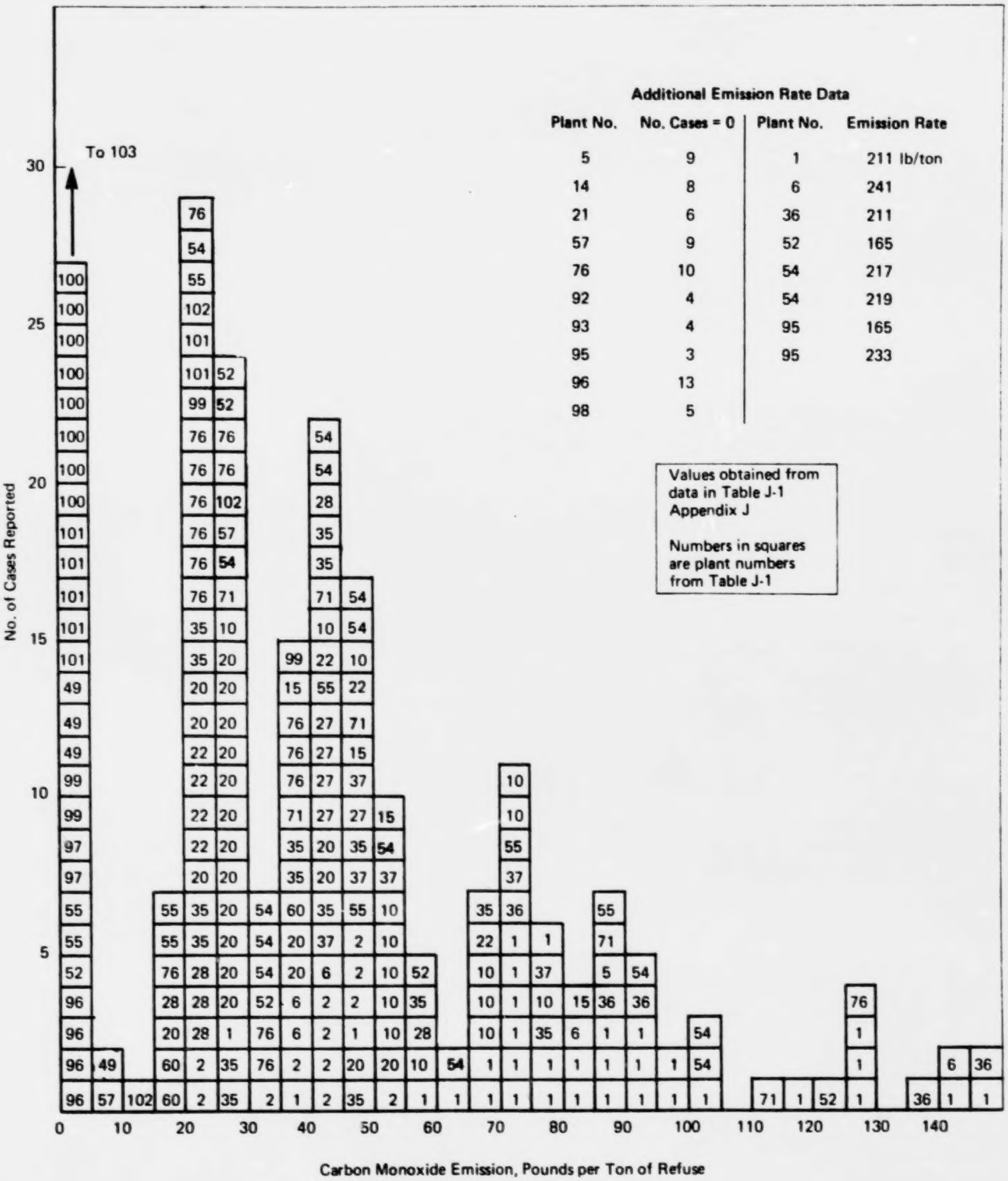
High percentages of combustible in the particulates leaving a combustion chamber are encountered during the incineration of wastes that generate a large volume of carbon-rich pyrolysis gases. For example, tests carried out by the PHS on an experimental incinerator, using as fuel asphalt-saturated felt roofing, resulted in emission of particulates with an average combustible content of 88%. Emission rates for combustible particulates will, of course, vary widely; reported values have ranged from 0.3 lb/ton waste for cellulosic materials to about 80 lb/ton for the asphalt-saturated roofing. For contemporary, continuous-feed municipal incinerators, an average emission of 3.9 lb combustible/ton refuse has been found, a figure which corresponds to about 20% of the total particulate.

The third type of combustible particulate emission is the aerosol of unreacted hydrocarbons which is formed when the pyrolysis products evolved on the grate are cooled and condensed before mixing with hot furnace gases. The white smokes that are produced usually consist of fine particles ($< 2\mu$) which are difficult to collect. Such emission, however, is relatively infrequent and can be eliminated by the adjustment of the air flow to a furnace to provide better overbed mixing.

*(2) Carbon Monoxide Emission.* Carbon monoxide is the most significant pollutant (on a weight basis) emitted from municipal incinerator furnaces, but unfortunately, existing air pollution control (APC) devices are ineffective for this pollutant. Since CO is produced by the incomplete combustion of gaseous pyrolysis products, the key to its control is improved mixing to assure oxidation of the CO in the combustion chamber. The time required in a well-mixed system to reduce the CO concentration from 1% to negligible values varies from less than a millisecond at 50% excess to about 0.035 second at 300% excess air. The average CO furnace emission rate, based on data from 33 incinerators (Figure III-4) was 38.6 lb/ton of refuse burned, or, grouping the data to produce an average value for each plant, 33.2 lb/ton. The estimated average emission factor for U.S. incinerators was 34.8 lb/ton.

*(3) Hydrocarbon Emission.* The hydrocarbon emission represents a relatively small fraction of the total emitted pollutant weight. However, because of their odor and contribution to photochemical smog formation, they must be curtailed. Because hydrocarbons oxidize rapidly to CO which, in turn, oxides slowly to $CO_2$, CO emission is always associated with hydrocarbon emissions. Although the converse is not always found to hold, the CO/hydrocarbon ratio where paired data are found may be used to estimate hydrocarbon emissions based on the much larger CO data bank. Data relating hydrocarbon and CO emissions is contained in Table V-10 (Ref. V-14, 15, 16) and the data from Table V-17 gives the average emission factor for hydrocarbons as 2.7 lb/ton.

*(4) Polynuclear Hydrocarbon Emission.* The polynuclear hydrocarbon (PNH) emission from municipal incinerators is small. Based on an assumed relationship between CO and PNH emissions the average PNH furnace emission factor is $5 \times 10^{-3}$ lb PNH/ton, 350 times greater than that ($1.17 \times 10^{-5}$ lb/ton of refuse) reported by the PHS (Chapter V, Ref. 36).



**Additional Emission Rate Data**

| Plant No. | No. Cases = 0 | Plant No. | Emission Rate |
|---|---|---|---|
| 5 | 9 | 1 | 211 lb/ton |
| 14 | 8 | 6 | 241 |
| 21 | 6 | 36 | 211 |
| 57 | 9 | 52 | 165 |
| 76 | 10 | 54 | 217 |
| 92 | 4 | 54 | 219 |
| 93 | 4 | 95 | 165 |
| 95 | 3 | 95 | 233 |
| 96 | 13 | | |
| 98 | 5 | | |

Values obtained from data in Table J-1 Appendix J

Numbers in squares are plant numbers from Table J-1

**FIGURE III–4 HISTOGRAM OF CALCULATED CARBON MONOXIDE EMISSION RATES (Pounds per Ton of Refuse)**

*(5) Nitrogen Oxide Emission.* The emission of nitrogen oxides (NOx) from municipal incinerators is also small. However, as the hydrocarbons, they contribute to photochemical smog conditions and must be considered. Figure III-5 summarizes the data reported in Appendix J on all available data on nitrogen oxide emissions. These data suggest an average emission factor of 3 lb/ton of refuse burned. Correlations shown in Chapter V indicate a possible relationship of the emission factor to furnace heat release rate.

*(6) Sulfur Oxides and Hydrogen Chloride Emissions.* The sulfur oxides are well recognized as among the prime pollutants of the air. The sulfur content of the average refuse was shown to be 0.0985% (Appendix C and Table IV-11). Based on the refuse analysis, the total sulfur oxide furnace emission rate is 3.94 lb/ton of refuse. The reported concentrations of $SO_3$ in incinerator flue gases are difficult to explain. Because of limited data and other uncertainties, no emission factor for $SO_3$ has been established.

The emission of hydrogen chloride (HCl) from incinerators not only concerns the public as an air pollutant, but the HCl presents a corrosion problem of importance to many incinerator and APC systems and thus must be considered by all incinerator system planners. The principal source of HCl in the incinerator effluent is the combustion of halogenated polymers, primarily polyvinyl chloride (PVC). Table III-5 shows the rapid rise to be expected in HCl emission from municipal incineration. However, the expected air pollution from this source may be limited by (a) HCl absorption by alkali ash materials in wet APC systems, and (b) HCl absorption in wet APC systems exhibiting good mass transfer characteristics.

*(7) Other Species.* Metals, such as lead, zinc, and cadmium, are volatile and have oxides volatile at incineration temperatures. Hence, these and other metals may also contribute to the air pollution problem. Other trace pollutants which may contribute to problems include hydrogen fluoride and selenium. In general, however, the emission rates for these pollutants are extremely small.

*(8) Emission Factor Summary.* The analysis of data described briefly above, and comprehensively in Chapter V, yielded estimates of typical emission factors for incinerators burning municipal solid waste. Although such estimates should not be applied to any one plant without due consideration of the details of operation and equipment, these typical emission factors are often usable in estimating total emissions within air quality regions, and so forth. Therefore, based on the mix of active U.S. incinerators (shown in Table I-1) and the mix of APC systems with their average control efficiencies (also from Table I-1), the average U.S. incinerator emission factors presented in Table III-6 was prepared.

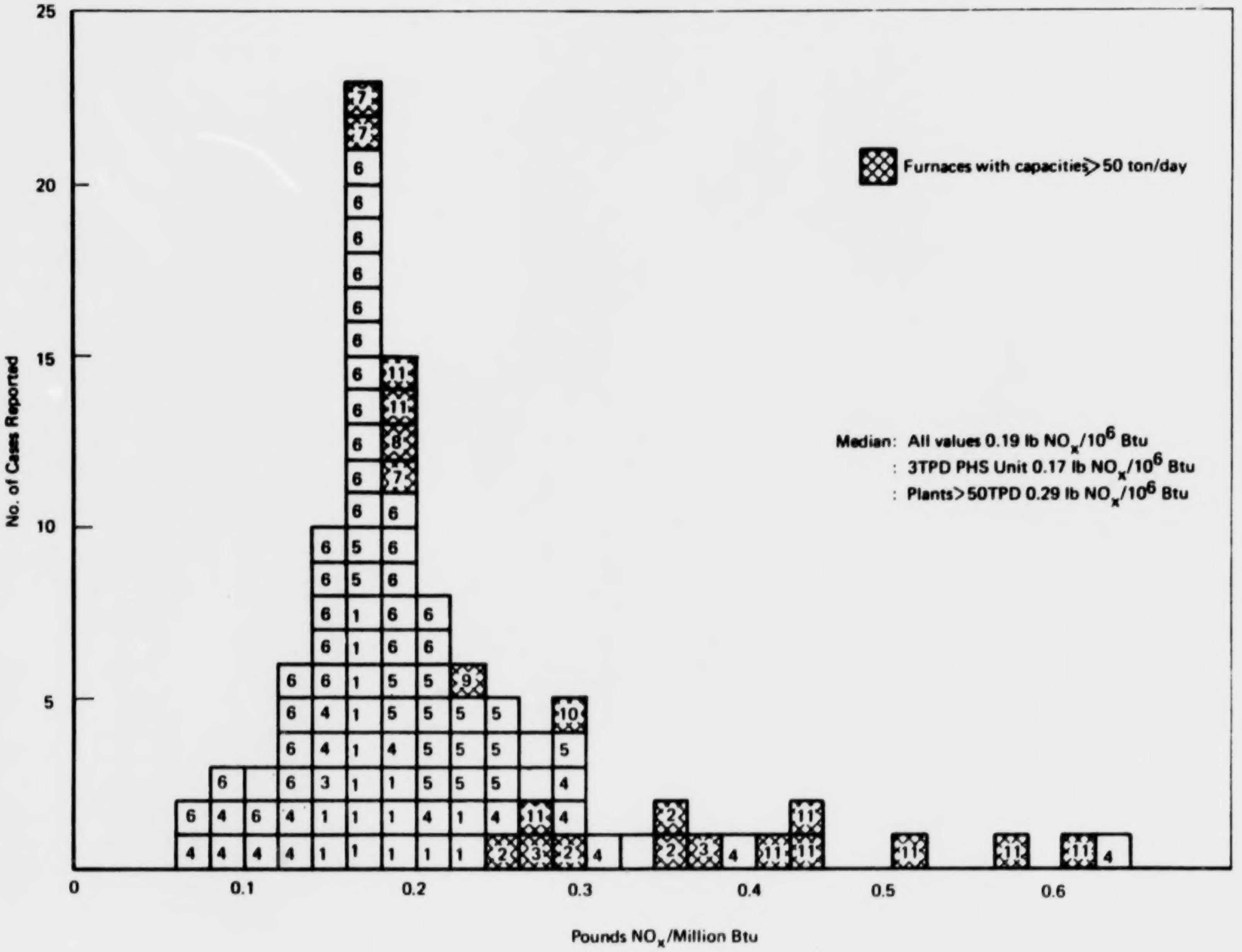


FIGURE III–5 HISTOGRAM OF EMISSION RATES OF NO$_x$ (as NO$_2$) RELATIVE TO HEAT RELEASE RATES

## TABLE III--5

## ANTICIPATED GROWTH PATTERNS OF PVC IN AVERAGE REFUSE AND ASSOCIATED HCl FURNACE EMISSION FACTORS*

| Year | % Plastics in Refuse** | % PVC Resin in Plastics | HCl Emission Factor lb HCl per Ton of Refuse*** |
|---|---|---|---|
| 1968 | 1.1 | 7.8 | 0.99 |
| 1970 | 1.3 | 10.0 | 1.50 |
| 1975 | 1.8 | 10.6 | 2.20 |
| 1980 | 2.7 | 8.7 | 2.71 |
| 1990 | 3.5 | 10.9 | 4.41 |
| 2000 | 4.2 | 11.2 | 5.44 |

* **Source:** ADL Estimates.

** As Discarded Basis – Semi-Seasonal State – as defined in Chapter IV (see Table IV-14).

*** Based on quantitative conversion of the chloride in PVC to HCl.

### c. Air Pollution from Incineration in the United States

Although air pollution from incineration may, at first glance, appear rather insignificant when compared to that ascribed to the power, transportation, and chemical/manufacturing industries, its significance increases when one considers that most incinerator systems are located within or very near the city complex. Recent air pollution estimates for New York City, for instance, showed that almost 20% of the pollutant emanated from local incinerators. To determine what the national air pollution emissions from incineration might be when projected to the year 2000, a mathematical model was devised by the ADL study team to predict future incinerator capacity and air pollution load. Figure III-6 is a flow diagram of the model. The initial step was to characterize the emission from a variety of incinerator types (Chapter V). The model was based on historical incinerator growth patterns (Appendix I), but modified to reflect growing solid-waste pressures and the diminishing availability of landfill sites. By combining estimates of the future growth rate of various incinerator types with a comparison estimate of APC systems, projections of total active incinerator capacity and total furnace and stack emissions were made at various levels of control. From the economic analysis described in Chapter VII, total investment and operating costs corresponding to these projections were also made.

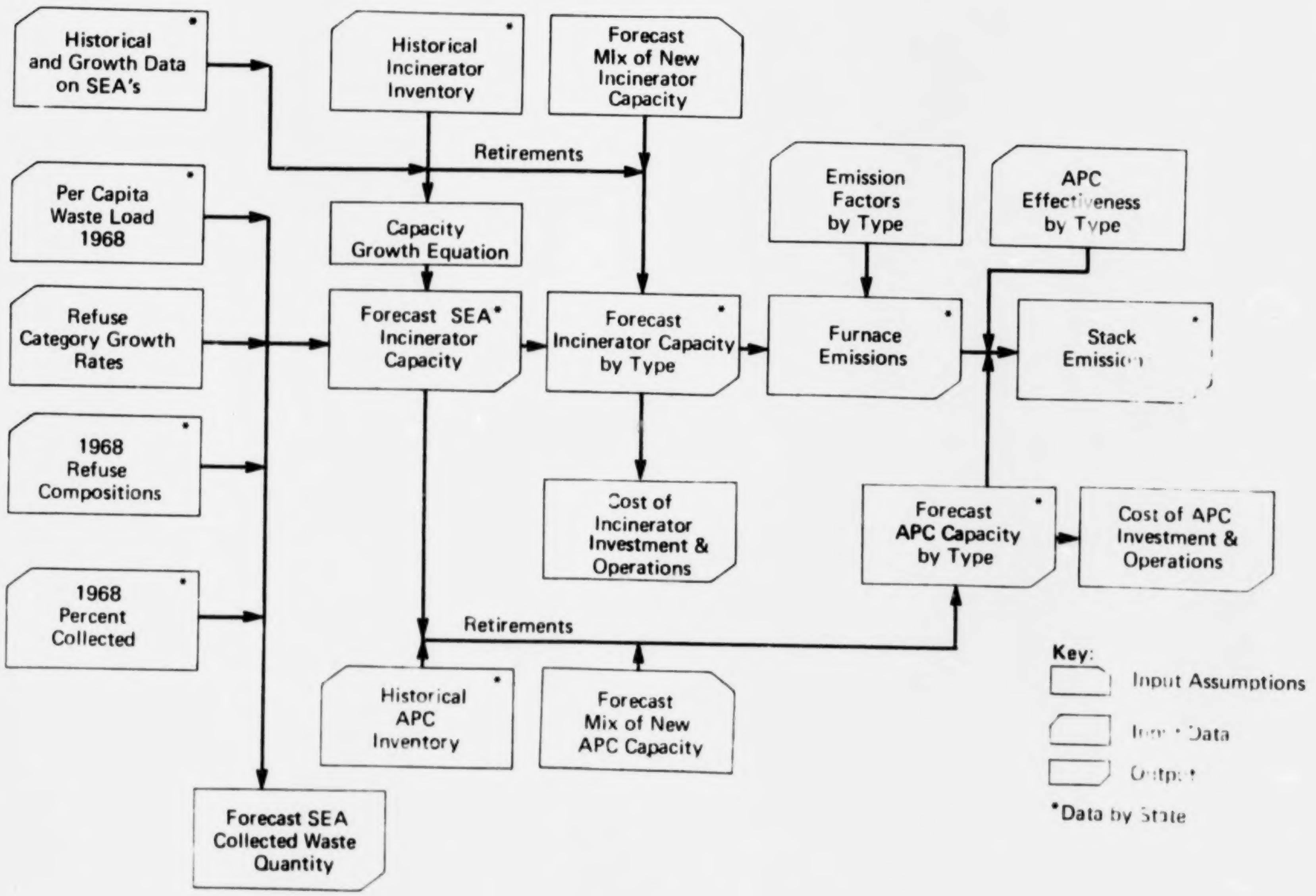

Historical and Growth Data on SEA's *
Historical Incinerator Inventory *
Forecast MIx of New Incinerator Capacity
Retirements
Per Capita Waste Load 1968 *
Capacity Growth Equation
Emission Factors by Type
APC Effectiveness by Type
Refuse Category Growth Rates
Forecast SEA* Incinerator Capacity
Forecast Incinerator Capacity by Type *
Furnace Emissions *
Stack Emissions *
1968 Refuse Compositions *
Cost of Incinerator Investment & Operations
Forecast APC Capacity by Type *
Cost of APC Investment & Operations
1968 Percent Collected *
Retirements
Historical APC Inventory *
Forecast Mix of New APC Capacity
Forecast SEA Collected Waste Quantity
Key:
Input Assumptions
Input Data
Output
*Data by State

FIGURE III–6 FLOW DIAGRAM OF MODEL

## TABLE III-6

## TYPICAL EMISSION FACTORS FOR U.S. INCINERATORS ACTIVE IN 1968

| | Pollutant | Furnace Emission* Factor (lb/ton of refuse) | Stack Emission* Factor (lb/ton of refuse) |
|---|---|---|---|
| 1. | Mineral Particulate | 15.1 | 9.5 |
| 2. | Combustible Particulate | 4.6 | 4.1 |
| 3. | Total Particulate | 19.7 | 13.6 |
| 4. | Carbon Monoxide | 34.8 | 34.8 |
| 5. | Nitrogen Oxides (as $NO_2$) | 3.0 | 2.6 |
| 6. | Hydrocarbons | 2.7 | 2.7 |
| 7. | Sulfur Oxides (as $SO_2$) | 3.9 | 3.9 |
| 8. | Hydrogen Chloride | 1.0 | 0.8 |
| 9. | Polynuclear Hydrocarbons | $5.0 \times 10^{-3}$ | $3.2 \times 10^{-3}$ |
| 10. | Volatile Metals (lead) | 0.03 | 0.03 |

*Based on weighing factors from the total active incinerator and incinerator APC inventory (Table I–1, Appendix I), average air pollution control efficiencies (Table III–8) and emission factors from Table V–17.

The model's input data (base year 1968) included (a) state economic area (SEA) statistics, (b) per capita waste generation rates (1968), (c) refuse compositions (1968) and projections (Chapter IV), (d) percentage of generated refuse collected, (Chapter IV, Table IV-1), (e) historical incinerator and incinerator APC inventory (Appendix I), (f) furnace emission factors (Table V-17), APC effectiveness, (Table VII-8), forecast mix of new incinerator and APC capacity (Table VI-2), and economic data (Table VI-2).

Although the authors admit to certain applicability qualifications and limitations in the model, the supporting data bank, and thus in its credibility (See Chapter VI-B-2), nonetheless the results provide a definite insight into the scope of the incinerator air pollution problem.

*(1) Incinerator Capacity Projection.* Figure III-7 (lower line) points to a fourfold increase in active U.S. incinerator capacity in the next 30 years at an average rate of 7000 TPD of new capacity per year. The upper line serves to incorporate accelerated incinerator growth factors, developed on a state-by-state basis, which increases the year 2000 projections by 40,000 TPD. Based on the historical model of incinerator growth, the anticipated increase in plant operating factor and capacity results in slightly over a 23% increase in the fraction of collected waste incinerated by the year 2000 (Figure III-8).

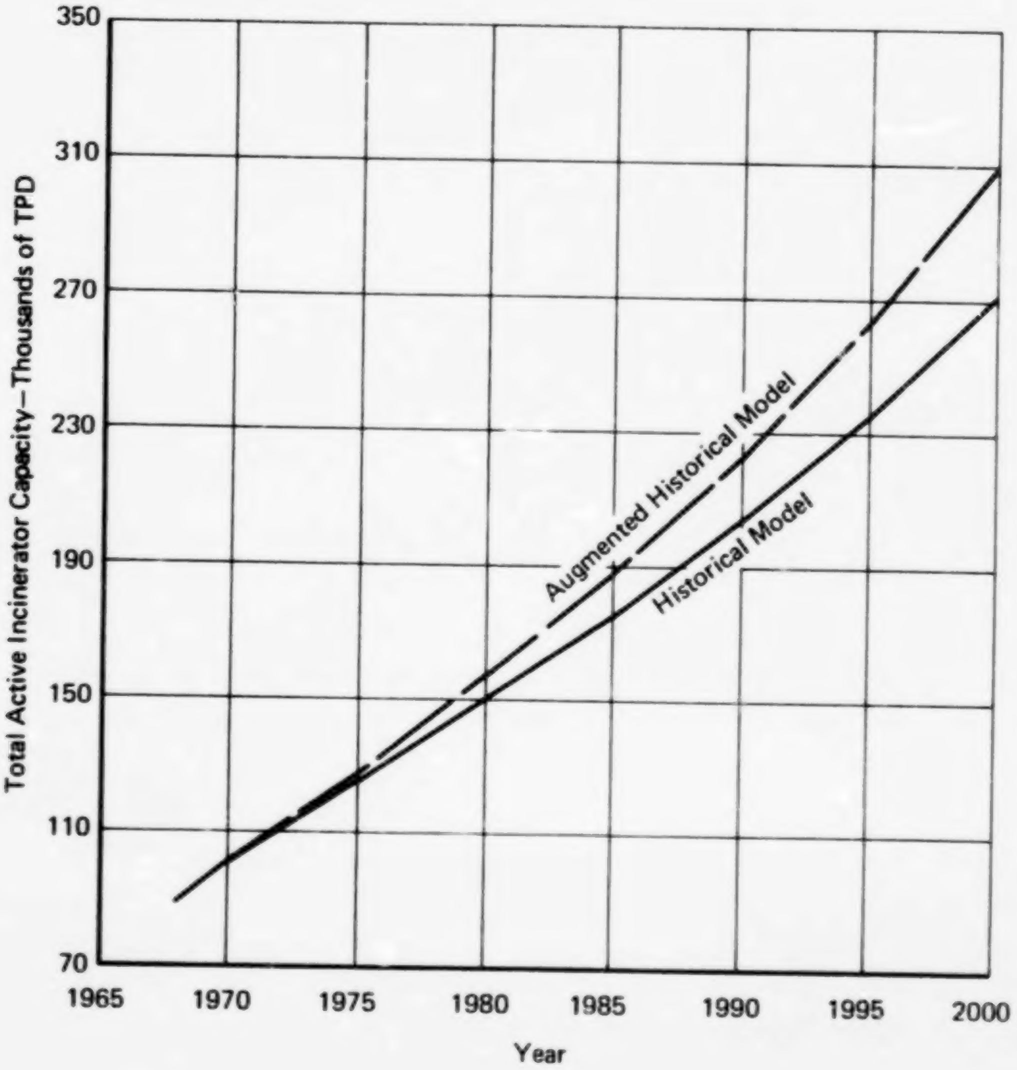


**FIGURE III–7** PROJECTIONS OF FUTURE ACTIVE INCINERATOR CAPACITY

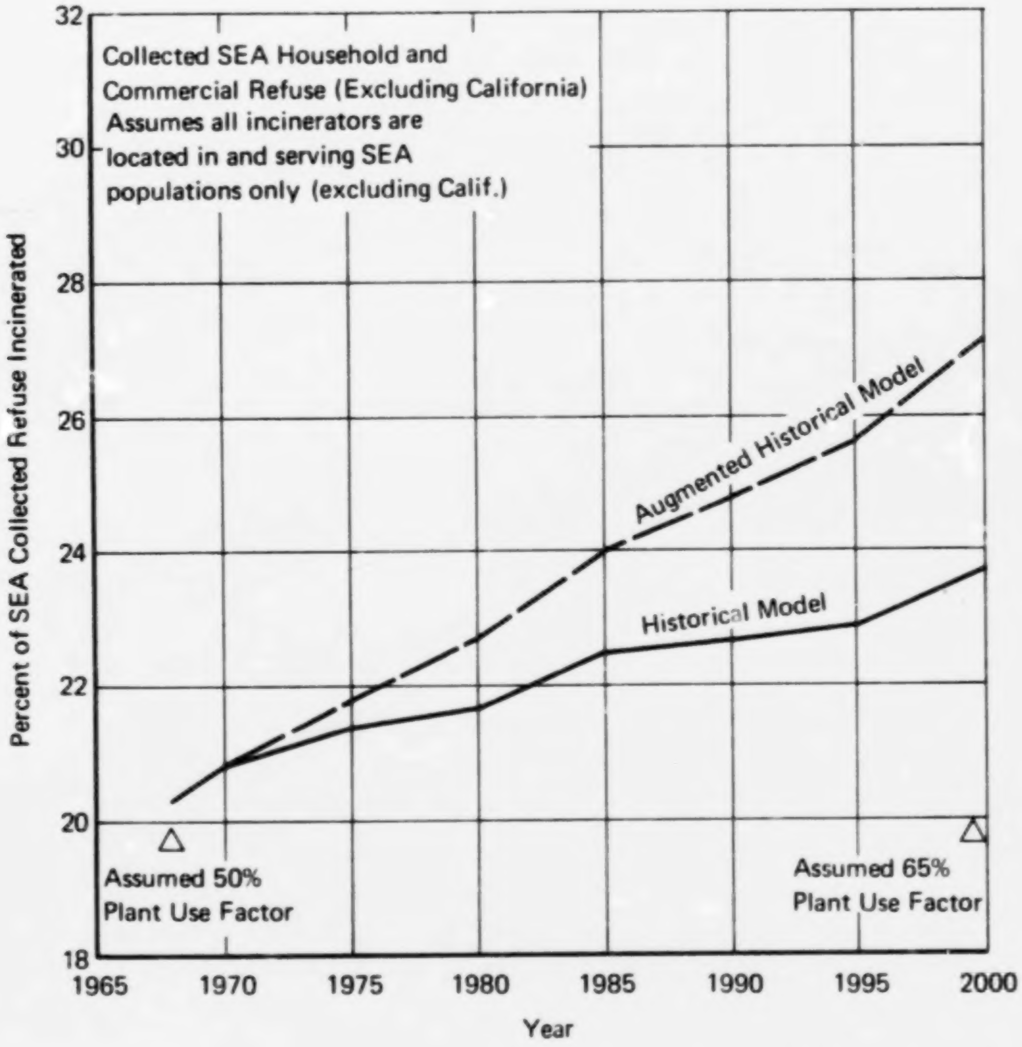


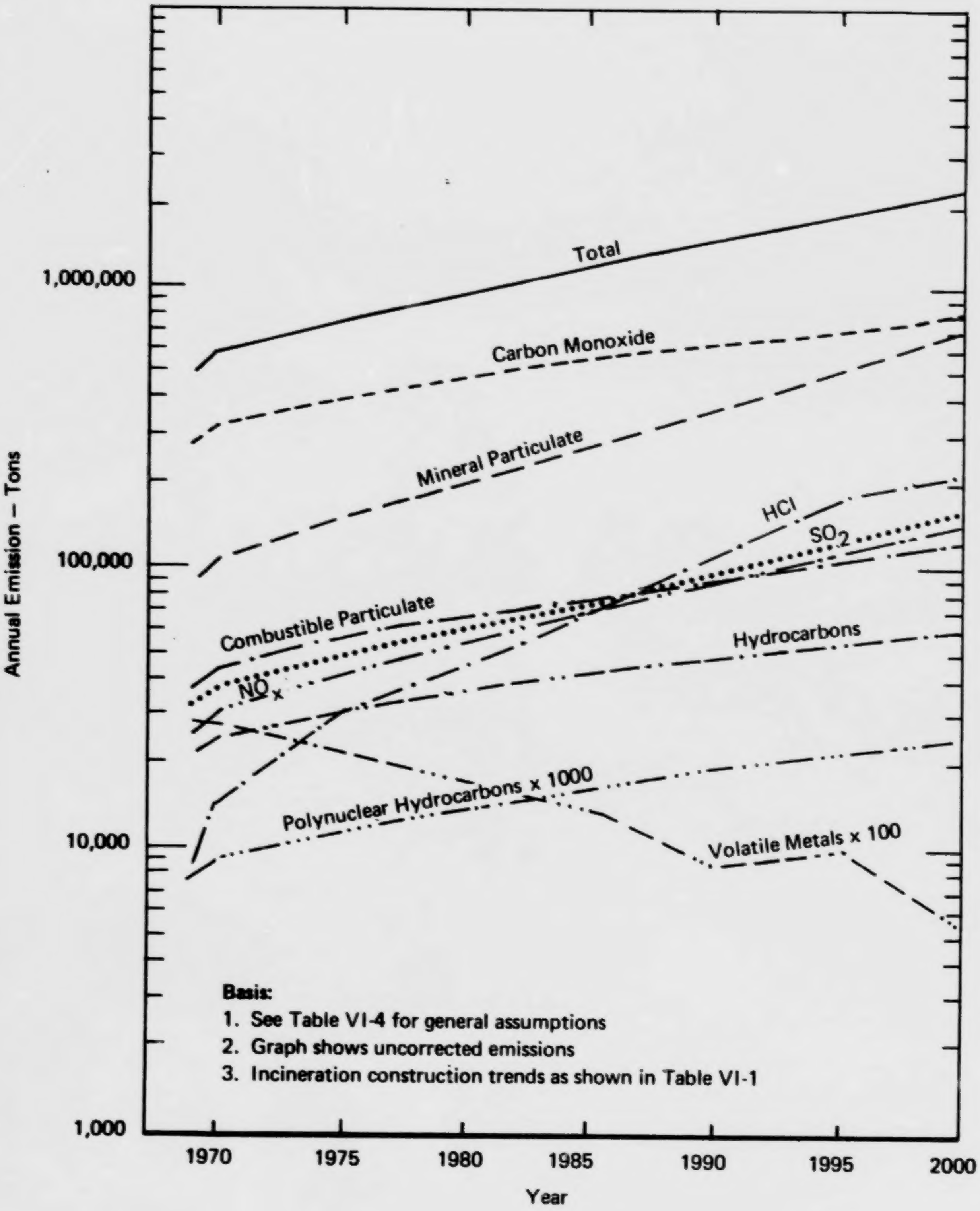
FIGURE III–8 PROJECTIONS OF FRACTION OF SEA-COLLECTED WASTE INCINERATED

*(2) Furnace Emission Projection.* Based on the use of the model, with the assumptions indicated in Table VI-2, and the accelerated incinerator growth rates, total uncontrolled furnace emission rates (Figure III-9) will approximate 580,000 tons per year, the majority being CO at 320,000 tons per year. Figure III-10 presents the estimated total emissions, on the assumption of the introduction of advanced incinerator concepts, particularly pyrolysis. The figure points to a modest 6% reduction in CO emissions and 13% in total pollution emissions by 2000.

*(3) Stack Emission Projections.* Based on the model's projection to the year 2000, mineral particulate emission tends to level off about 1990, and the growth rate of total HCl emissions first slows down, but then accelerates rapidly (on the assumption of an increase and then a decrease in the use of wet collectors). As for furnace emissions, no substantial decrease in total emissions is foreseen by rapid introduction of new concepts.

To visualize the impact of more rigorous mineral particulate APC efficiency standards, total U.S. emissions were forecast for various assumptions as to the average efficiency of the APC systems for plants built post-1968. The attendant decreases in the air pollution quotient were then calculated. A series of graphs in Chapter VI presents an overall picture of the stack emission projections to the year 2000. Total annual particulate pollutant stack emission estimates for U.S. municipal incineration at various levels of control are presented in Figure III-11 and the total annual combustible emission estimates for U.S. municipal incineration are presented in Figure III-12. It should be noted that these projections do not include the effects of improving APC equipment particulate control efficiency on existing plants (which could markedly reduce particulate emissions over the next decade). Also, these projections do not assume the introduction of technology to reduce (by in-furnace combustion) combustible pollutant emissions. Such technology (mainly affecting the turbulence level in furnaces) could reduce combustible emissions by 25-75% from those shown in Figure III-12.

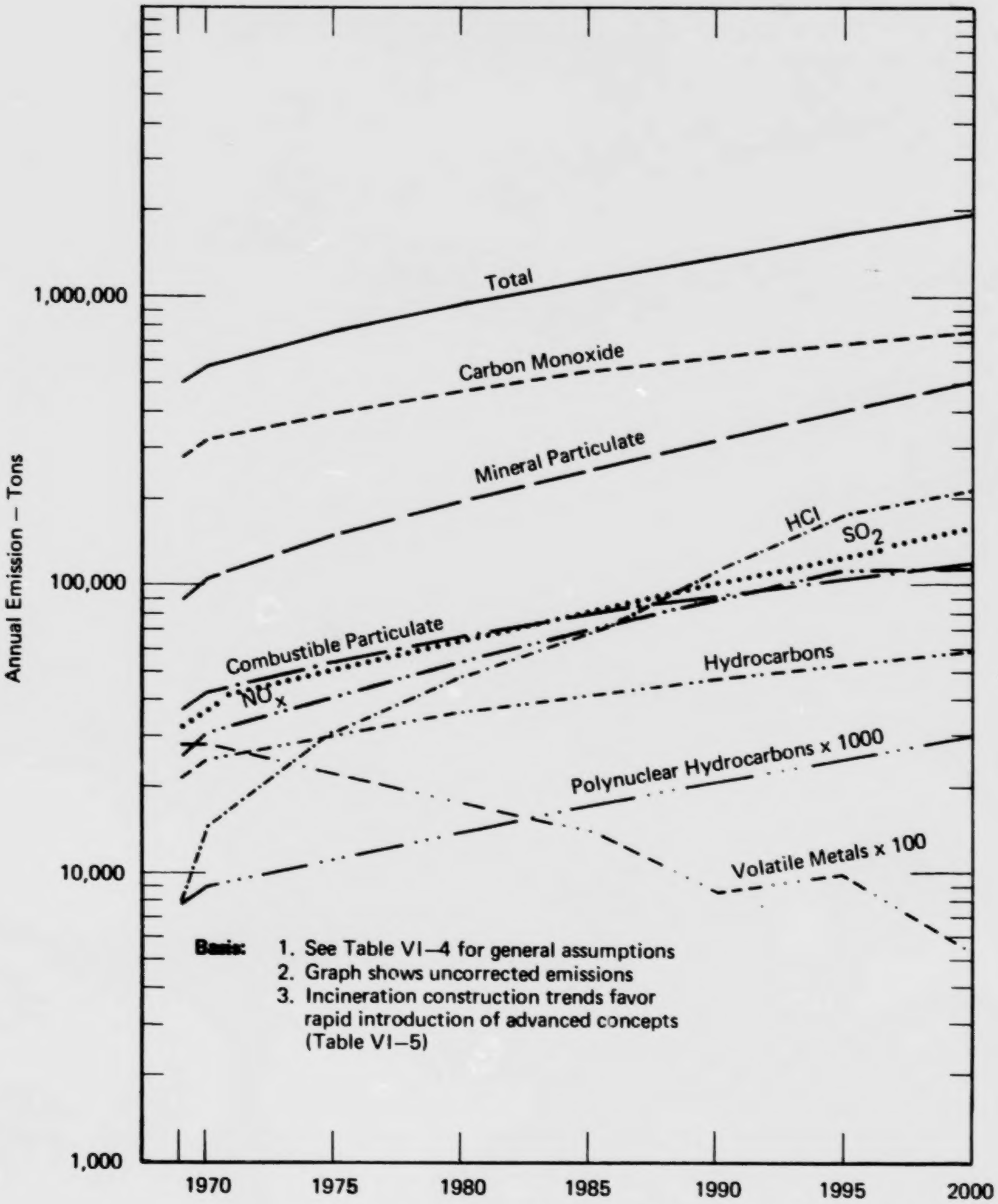
*(4) Economic Implications.* APC equipment and operation costs approximate 10% of both the capital and operating costs of a typical large municipal incinerator facility. Projections point, with reasonable accuracy, to the relatively small costs to improve air pollution control relative to the total costs of the incinerator facility.



**Basis:**

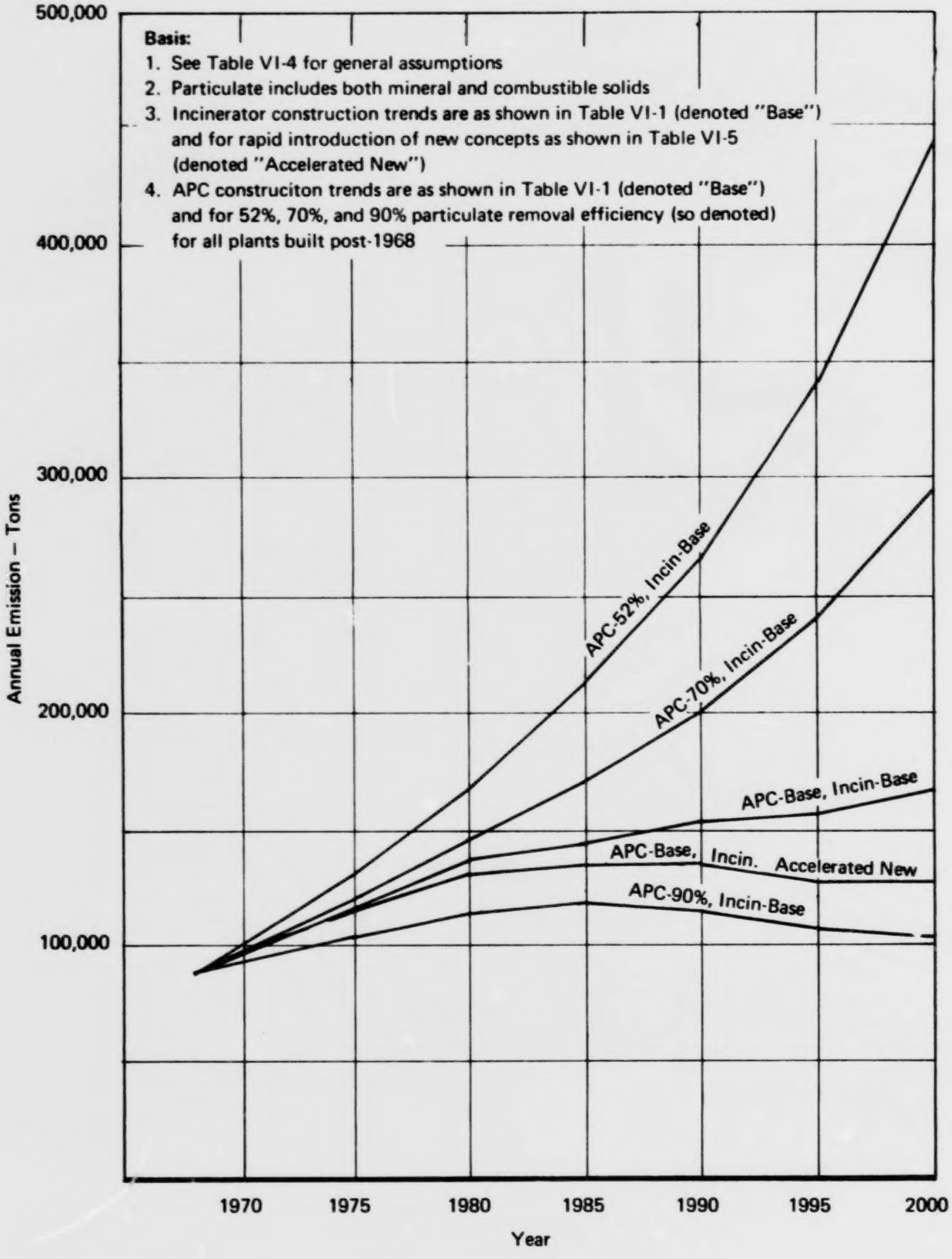
1. See Table VI-4 for general assumptions
2. Graph shows uncorrected emissions
3. Incineration construction trends as shown in Table VI-1

FIGURE III–9 TOTAL ANNUAL FURNACE EMISSION ESTIMATES FOR U.S. MUNICIPAL INCINERATION SYSTEMS



**Basis:** 1. See Table VI–4 for general assumptions
2. Graph shows uncorrected emissions
3. Incineration construction trends favor rapid introduction of advanced concepts (Table VI–5)

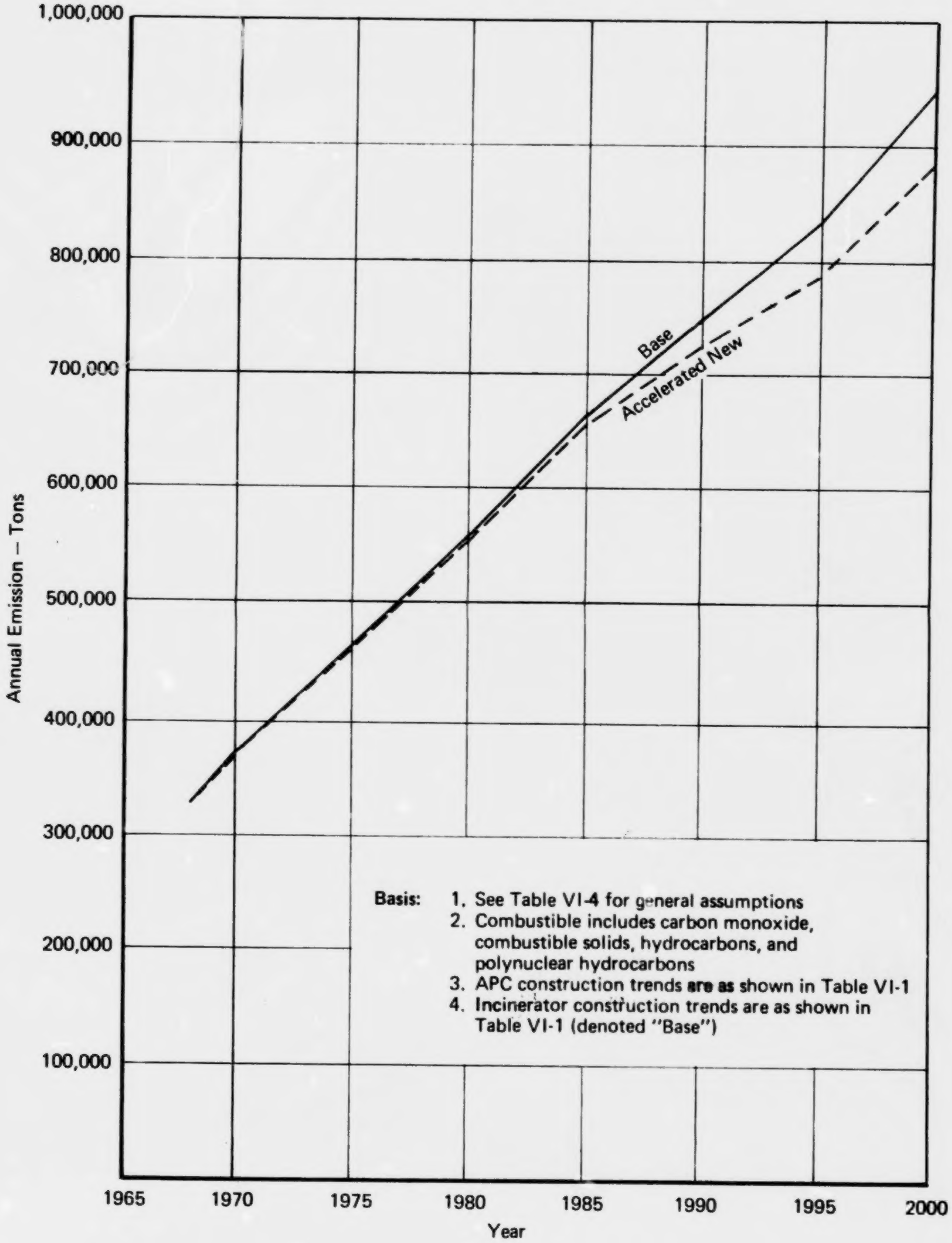
FIGURE III–10 TOTAL ANNUAL FURNACE EMISSION ESTIMATES FOR U.S. MUNICIPAL INCINERATOR SYSTEMS ASSUMING RAPID INTRODUCTION OF ADVANCED TECHNIQUES



**Basis:**

1. See Table VI-4 for general assumptions
2. Particulate includes both mineral and combustible solids
3. Incinerator construction trends are as shown in Table VI-1 (denoted "Base") and for rapid introduction of new concepts as shown in Table VI-5 (denoted "Accelerated New")
4. APC construciton trends are as shown in Table VI-1 (denoted "Base") and for 52%, 70%, and 90% particulate removal efficiency (so denoted) for all plants built post-1968

FIGURE III--11 TOTAL ANNUAL PARTICULATE POLLUTANT STACK EMISSION ESTIMATES FOR U.S. MUNICIPAL INCINERATION – AT VARIOUS LEVELS OF CONTROL



**Basis:**
1. See Table VI-4 for general assumptions
2. Combustible includes carbon monoxide, combustible solids, hydrocarbons, and polynuclear hydrocarbons
3. APC construction trends are as shown in Table VI-1
4. Incinerator construction trends are as shown in Table VI-1 (denoted "Base")

FIGURE III–12 TOTAL ANNUAL COMBUSTIBLE EMISSION ESTIMATES FOR U.S. MUNICIPAL INCINERATION

### d. Technical-Economic Analysis of the Air Pollution Aspects of Municipal Incineration

Most incineration plants have been built primarily to reduce the volume of solid waste and to sterilize it, with little heed paid to the concomitant pollution of the air. Air pollution control of any type has generally been a corrective action. Today, however, the public has become outraged at the increased pollution of the air, and municipalities are hence beginning to take a closer look at pollution abatement controls.

The primary air pollutants emanating from the incineration of solid wastes are mineral particulates, combustible solids and gases, and noncombustible gases. Incinerator design and operating practices have little effect on particulate emission, but an air pollution control system can control such emissions effectively. On the other hand, the design and operating practices of a given incinerator can have a marked effect on the emission of combustible solids and gases which may be only slightly abated by an APC system. Noncombustible gaseous pollutant emissions also are little affected by design and operation consideration, but can be somewhat affected by the APC system, depending on the type. Basically these emissions are a strong function of the refuse composition.

*(1) Air Pollution Control for Incinerators.* The emission of mineral particulates is controlled most effectively by incinerator APC systems which are the only means of reducing stack concentrations of noncombustible gaseous pollutants. APC devices are selected on the basis of a compromise between the initial capital investment required, the cost of operation, and the efficiency of collection. Operating characteristics, reliability, and water pollution potential play lesser roles in the selection procedure.

Settling chambers are the simplest and least expensive of the APC systems now used to remove particulate pollutants. Basically, this chamber slows the flue gases (no temperature reduction necessary) to permit gravity settling of the coarse particulate. The calculated performance of a settling chamber (nominal dust size and density, 30-feet high, and a 5-second residence time) is shown in Table VII-8. The efficiency of this "perfect" chamber is about 41%; realistically it would probably be closer to 21%. Operation with wet floors and baffling would tend to increase the efficiency of a settling chamber, of course, but the best that could be expected is 35 % removal. Problems associated with dry settling chambers include manual dust removal, and consequent plant shutdown, water pollution and corrosion from water sluicing for the wet-bottom types, and the gross infiltration of tramp air (which often occurs in these chambers) which would tend to cool the flue gas and quench the combustion reactions, thus causing the emission of odorous hydrocarbon pollutants.

Other devices used to collect particulate emissions include mechanical collectors, such as the cyclone device (page VII-23) and electrostatic precipitators which separate the dust particles from the effluent by interaction of electrical charges placed upon the surface of the dust particles. As an example of the effectiveness of this technique, the performance of electrostatic precipitators operating on the Munich-North incinerator in West Germany is shown in Table III-7.

Fabric filters, properly designed and operated, are actually more effective in the removal of particulate matter than any of the conventional APC systems. The particulate collection efficiency of these devices often exceeds 99%. Also, some absorption of HCl may take place on the alkaline fly ash material in the dust cake. References 21-23 of Chapter VII describe the collection mechanisms in detail. For satisfactory performance and long bag life, in combustion system applications, however, flue gas temperatures have to be maintained in the 250-550°F range (Appendix B).

Various types of scrubbing devices are currently used for contacting liquids with gas streams to remove particulate matter and gaseous pollutants. These include wetted surfaces, liquid sprays, and bubbling gas devices. The wetted surface and liquid spray devices are more prominently used in municipal incinerators. However, all such devices are noted for their side effects in humidifying and cooling the gas, thus producing a steam plume at the stack under certain atmospheric conditions. (This is often misinterpreted by the public as a vestige of air pollution; see Appendix B for more information on the plume formation problem.) Another characteristic of the scrubbers is that, for a given dust, a higher degree of particulate removal generally results from the application of more power per unit of gas fed (greater pressure drop and hence greater operating cost). Waste water disposal can also be a serious problem as is corrosion due, in part, to the collection of acidic gases (HCl, $SO_2$, and $NO_2$). Average efficiency values for various APC devices for the pollutants of interest in municipal incineration are shown in Table III-8.

In general, gaseous pollutants will pass unchanged through the dry control devices, except the bag filters which have purportedly absorbed as much as 90% of the $H_2SO_4$ values but little of the $SO_2$. Wet control devices, although primarily used as particulate removal agents, will remove some of the gaseous pollutants. However, most wet scrubber devices are less effective than a single-equilibrium contact. Analyses have shown that particulate scrubbers can be expected to remove – in addition to particulates – a portion of the $H_2SO_4$, HCl, $SO_2$, organic acids, and $NO_2$. Other components – CO, $CO_2$, NO, hydrocarbons, aldehydes, and $SO_3$ – are essentially untouched by scrubbing. Most simple, low-energy, co-current scrubbers operate at gaseous pollutant removal levels less than one

## TABLE III–7

## PERFORMANCE OF ELECTROSTATIC PRECIPITATOR OPERATING ON MUNICH–NORTH I INCINERATOR IN WEST GERMANY (ref. 2)

| Location | Fuel | Gas Velocity m/sec | Guaranteed Efficiency (%) | Actual Efficiency (%) | Apparent Drift Velocity, w(cm/sec) |  |  |
|---|---|---|---|---|---|---|---|
|  |  |  |  |  | Corresponding to Guarantee | Corresponding to Actual Measured | Ratio $\left(\frac{w_{actual}}{w_{guaranteed}}\right)$ |
| Munich | Coal | 0.845 | 97.94 | 99.56 | 4.40 | 6.21 | 1.41 |
| Munich | Coal | 0.871 | 97.49 | 98.67 | 3.42 | 5.10 | 1.49 |
| Munich | Coal & Refuse | 1.132 | 99.25 | 99.75 | 7.50 | 9.20 | 1.23 |
| Munich | Refuse | 0.490 | – | 99.89 | – | 4.51 | – |

theoretical stage. Their efficiency may be improved substantially, however, with the use of high-energy systems with water treatment to increase gas solubility and to reduce corrosion. Average efficiency values for various APC devices for the pollutants of interest in municipal incineration are shown in Table III-8.

The total investment costs for APC systems in incinerator applications are shown in Figure III-13. Annual operating costs of the various APC systems discussed are presented in Figure III-14 for two shifts per day operation. The basis for these costs is presented in the Introduction to Chapter VII. The costs are based on discussions with vendors, review of the literature, and analysis of plant data.

The selection of an APC system must be made on a case-by-case basis, taking into consideration the unique character of each plant location and plant performance objectives established by the community. The most important determinant in the selection of the system is the maximum amount of pollutant permitted to enter the atmosphere. Other criteria that must be considered in meeting an efficiency objective include investment versus operating cost trade-offs; constraints such as utilities cost and availability; operator qualifications; steam plume formation ramifications; foundation requirements; and waste-water disposal problems.

Efficiency requirements for any APC system are necessarily based on an estimation of entrance loadings. Modification of plant equipment and/or operating practices should also be considered with a view to reducing the inlet loading and thereby the efficiency requirements (and cost). The trade-offs between efficiency and cost are illustrated in Figure III-15 in addition to efficiency and cost considerations, certain other considerations, such as space, have to be considered. For example, the relative in-plant space requirements for average air pollution control systems are shown in Table III-9.

*(2) Aspects of Modification to Existing Plants.* In view of the replacement value of existing incineration facilities – in the neighborhood of some $500 million – it is safe to say that initial efforts at reducing the air pollution problems of municipal incineration must be implemented in the old – not a new – facility. The cost of modifying an existing incinerator will vary widely. In some cases, major modifications will have to be made to the facility; in others, changes in operating practices may effect the control objective. In all cases, modifications should be evaluated carefully since the solution to one problem could be the cause of another. The overall goals of solid waste disposal, minimum cost and environmental pollution, and maximum safety reliability, and residue quality must dictate ultimate action. The high emission factors for contemporary systems suggests, however, that air pollution reduction has been given too low a priority in the past.

## TABLE III–8
## AVERAGE CONTROL EFFICIENCY OF APC SYSTEMS

| APC Type | APC System Removal Efficiency (weight percent) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Mineral Particulate | Combustible Particulate[a] | Carbon Monoxide | Nitrogen Oxides | Hydro-carbons | Sulfur Oxides | Hydrogen Chloride | Polynuclear Hydrocarbons[b] | Volatile Metals[c] |
| None (Flue Settling Only) | 20 | 2 | 0 | 0 | 0 | 0 | 0 | 10 | 2 |
| Dry Expansion Chamber | 20 | 2 | 0 | 0 | 0 | 0 | 0 | 10 | 0 |
| Wet Bottom Expansion Chamber | 33 | 4 | 0 | 7 | 0 | 0 | 10 | 22 | 4 |
| Spray Chamber | 40 | 5 | 0 | 25 | 0 | 0.1 | 40 | 40 | 5 |
| Wetted Wall Chamber | 35 | 7 | 0 | 25 | 0 | 0.1 | 40 | 40 | 7 |
| Wetted, Close-Spaced Baffles | 50 | 10 | 0 | 30 | 0 | .5 | 50 | 85 | 10 |
| Mechanical Cyclone (dry) | 70 | 30 | 0 | 0 | 0 | 0 | 0 | 35 | 0 |
| Medium-Energy Wet Scrubber | 90 | 80 | 0 | 65 | 0 | 1.5 | 95 | 95 | 80 |
| Electrostatic Precipitator | 99 | 90 | 0 | 0 | 0 | 0 | 0 | 60 | 90 |
| Fabric Filter | 99.9 | 99 | 0 | 0 | 0 | 0 | 0 | 67 | 99 |

(a) Assumed primarily $< 5$ microns.

(b) Assumed two-thirds condensed on particulate, one-third as vapor.

(c) Assumed primarily a fume $< 5$ microns.

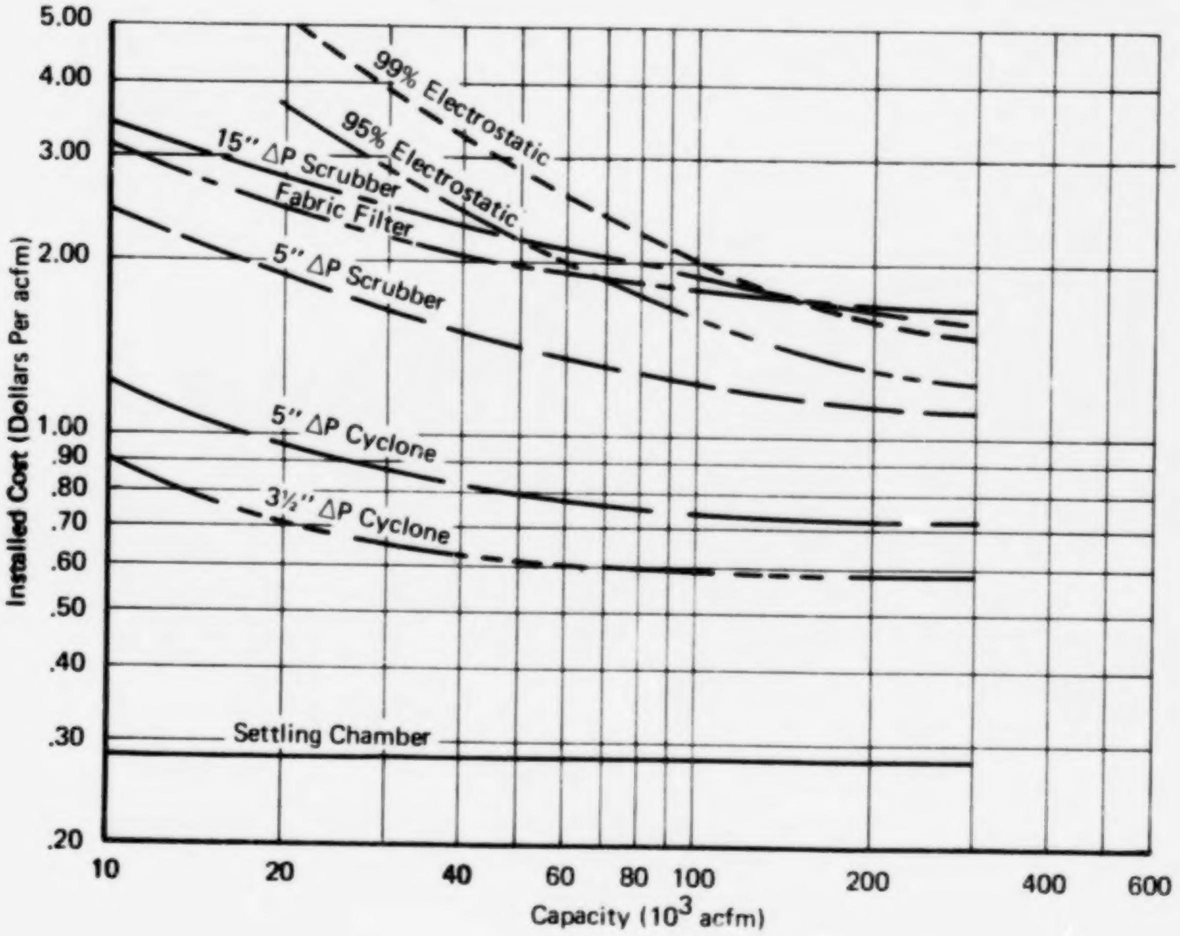


FIGURE III–13 AIR POLLUTION CONTROL SYSTEMS – TOTAL INSTALLED COSTS

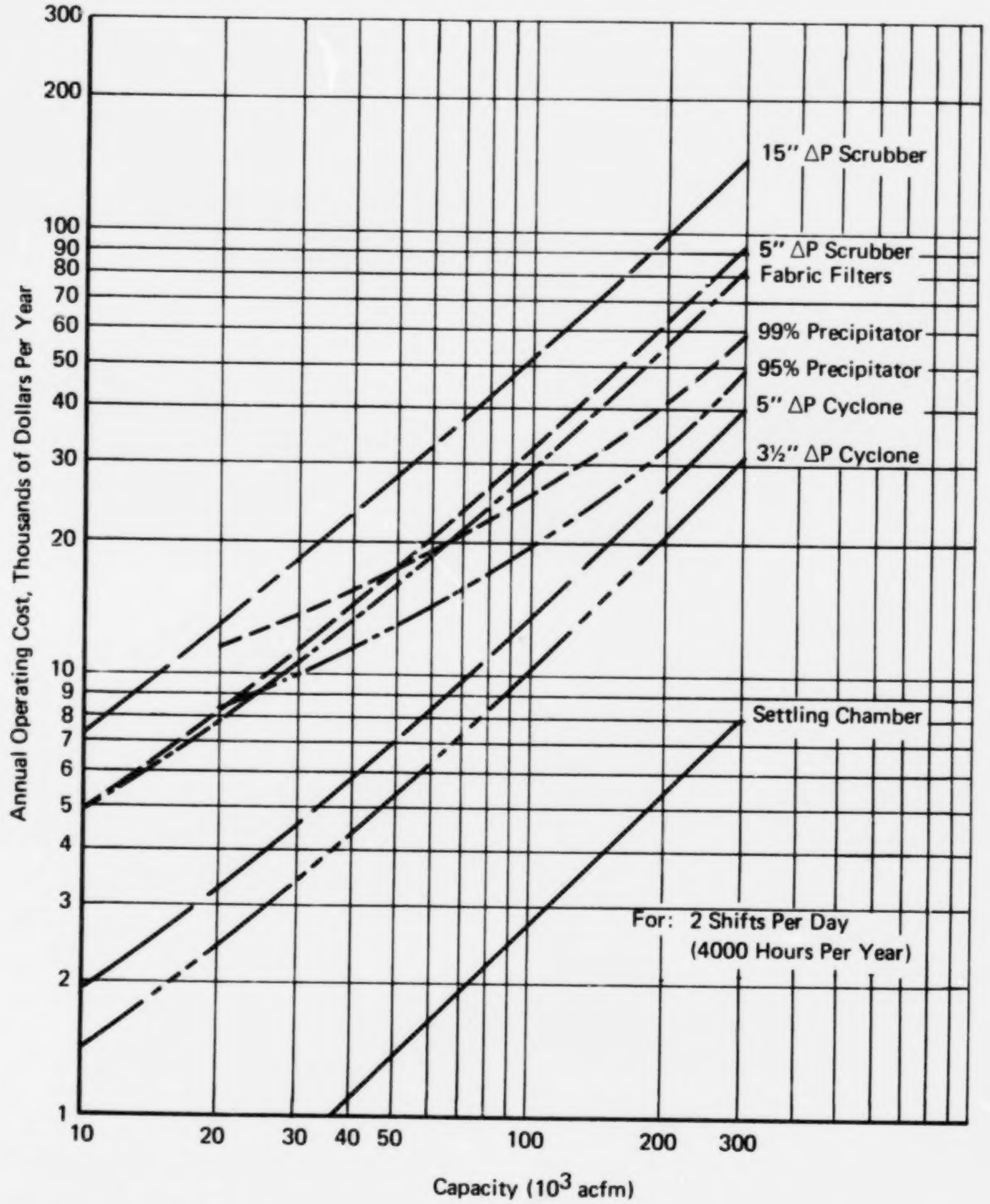


FIGURE III–14 AIR POLLUTION CONTROL SYSTEMS ANNUAL OPERATING COSTS

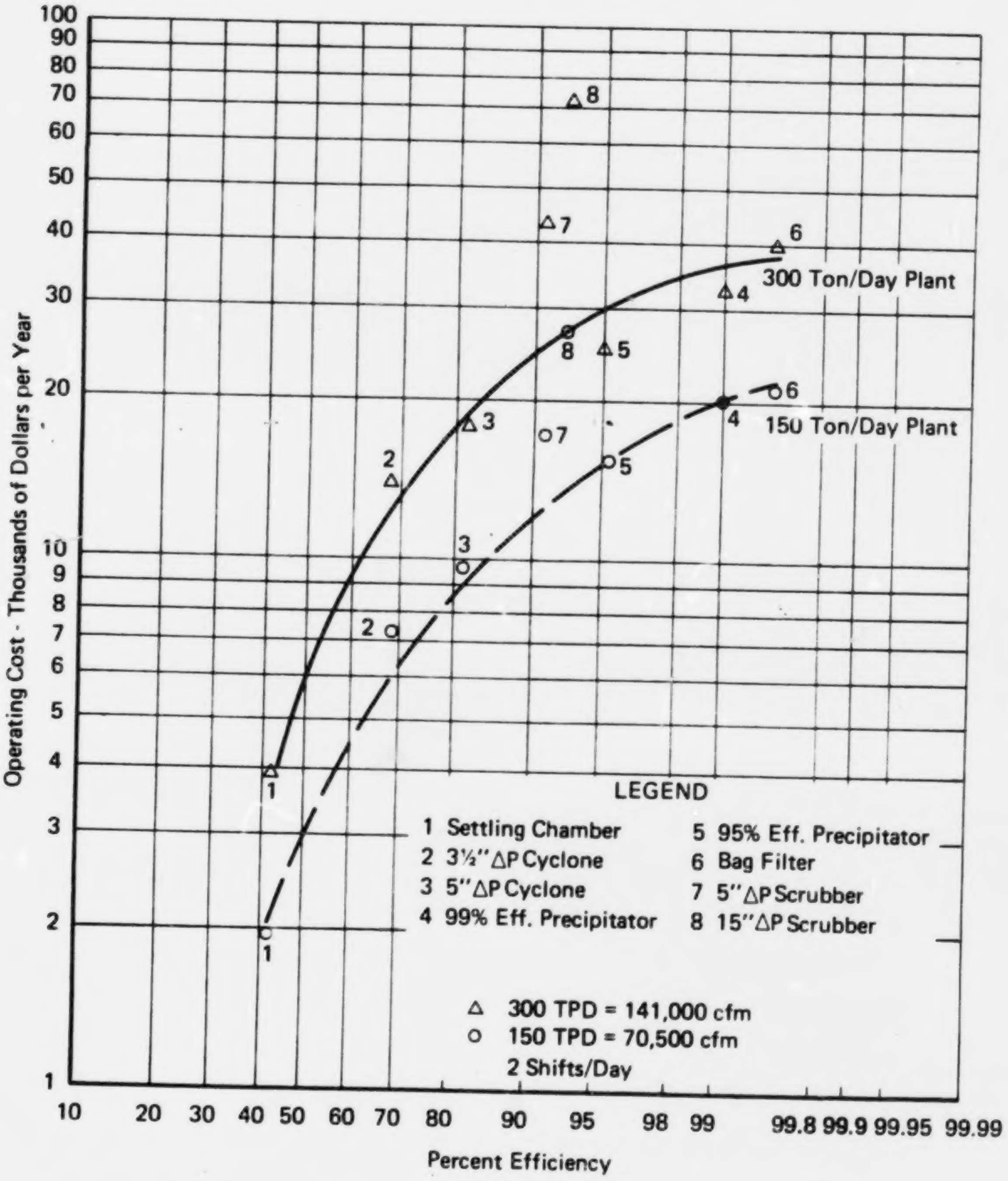


FIGURE III–15 TOTAL ANNUAL OPERATING COST VS. PARTICULATE REMOVAL EFFICIENCY

## TABLE III–9

## RELATIVE IN-PLANT SPACE REQUIREMENTS FOR AVERAGE AIR POLLUTION CONTROL SYSTEMS[39]

| Equipment Type | Relative Space Requirement |
|---|---|
| Electrostatic Precipitator | 90% |
| Scrubber – Spray type | 50% |
| Flooded Plate | 30% |
| Venturi | 25% |
| Mechanical Cyclone – Multiclone | 25% |
| 60" dia. tangential inlet | 30% |
| wetted wall | 25% |
| Baghouse filter | 100% |
| Settling chamber with sprays | 60% |

A method to aid the municipal incineration facility manager in determining the most efficient APC system for his facility has been devised by the ADL study team. The method was designed to:

- Indicate the symptoms of poor incinerator performance as an aid in air pollution problem evaluation;
- Describe the causes for each symptom of poor incinerator performance as an aid in suggesting aspects of the plant design or operating practices which could underlie the symptom;
- Suggest modifications of the plant or alternate operating procedures to correct such deficiencies, and evaluate the potential cost and effectiveness of the corrective action; and
- Alert the problem-solver to the implications of a given corrective action relative to other aspects of overall performance.

Appendix K treats the whole subject of causes and cures for incinerator deficiencies affecting criteria of performance in depth. Figure III-16 is a decision diagram which can be used for incinerator performance improvement.

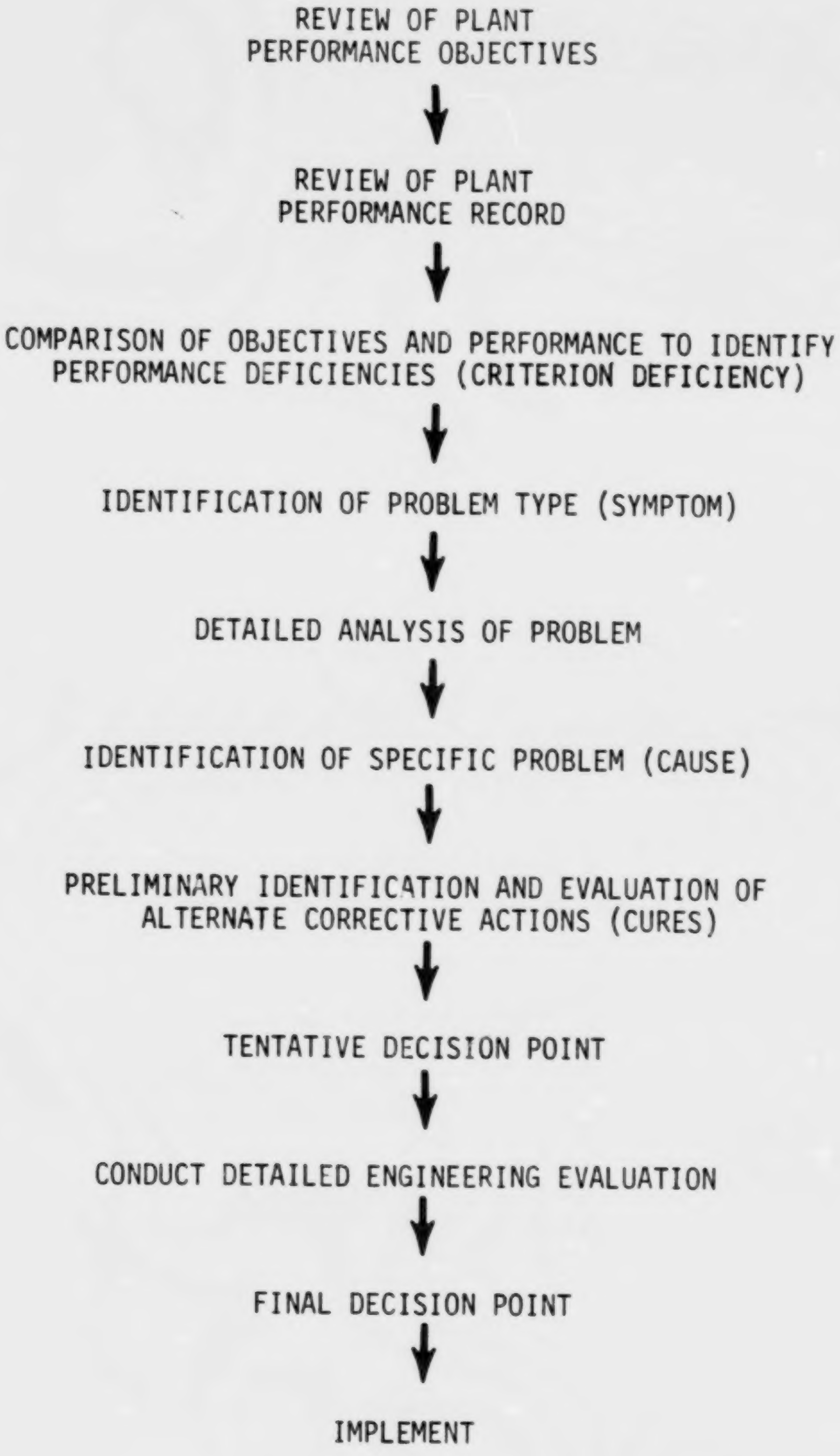

REVIEW OF PLANT PERFORMANCE OBJECTIVES
REVIEW OF PLANT PERFORMANCE RECORD
COMPARISON OF OBJECTIVES AND PERFORMANCE TO IDENTIFY PERFORMANCE DEFICIENCIES (CRITERION DEFICIENCY)
IDENTIFICATION OF PROBLEM TYPE (SYMPTOM)
DETAILED ANALYSIS OF PROBLEM
IDENTIFICATION OF SPECIFIC PROBLEM (CAUSE)
PRELIMINARY IDENTIFICATION AND EVALUATION OF ALTERNATE CORRECTIVE ACTIONS (CURES)
TENTATIVE DECISION POINT
CONDUCT DETAILED ENGINEERING EVALUATION
FINAL DECISION POINT
IMPLEMENT

**FIGURE III-16**

DECISION DIAGRAM FOR PERFORMANCE IMPROVEMENT

*(3) Incineration Concepts Based on Existing Technology.* In view of the increased emphasis being placed on municipalities to build incineration facilities – or to modify existing facilities with APC devices – an appreciation of the merits of the various incineration concepts will permit the municipalities to make well-founded decisions on a plant best suited to their individual needs. The principal criteria applicable to incineration which must be considered in making a choice of this type include reliability, residue quality, environmental pollution, safety, and cost (Appendix H, Section D). Once the level of performance desired in a particular incineration system has been established, then the technical and economic aspects must be considered. Eleven major incineration concepts are discussed in depth in Chapter VII. They include:

- Batch Feed
- Continuous Feed – Rectangular Construction
- Continuous Feed – Horizontal Cylindrical Construction
- Continuous Feed – Ignition Grate plus Burnout Kiln Construction
- Continuous Feed – Volatilizing Kiln and Burnout Grate Construction
- Continuous Feed – Three-Stage Rotary Kiln Construction
- Continuous Feed – Waterwall Construction
- Continuous Feed – Waterwall Construction/Suspension Burning
- Semi-continuous Feed – Package Incineration
- Semi-continuous Feed – Rotary Grate Construction
- Continuous Feed – Residue Fusion

As an example of the method used to present economic data, the investment cost and the estimated total cost of incineration using a continuous-feed (rectangular construction) incineration system is presented in Figure III-17 and Table III-10, respectively. The characteristics of the various concepts are summarized in Table III-11 on a relative scale of 1 (highly unfavorable) to 5 (highly favorable). The wide diversity of incinerator performance in incinerator systems is clearly evident in the table.

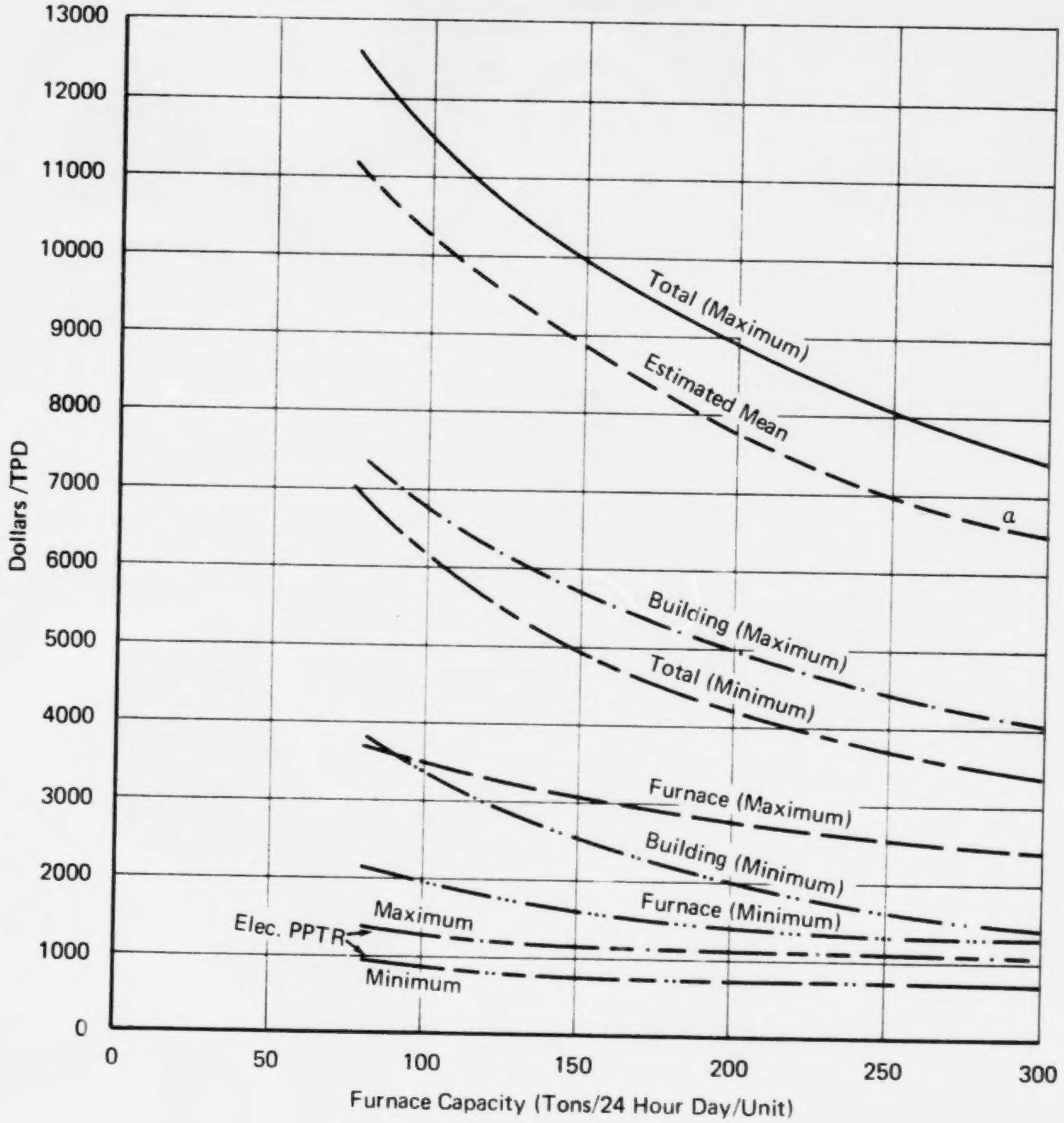


FIGURE III–17 AVERAGE INVESTMENT COSTS: CONTINUOUS FEED SYSTEMS RECTANGULAR CONSTRUCTION

## TABLE III–10

## ESTIMATED COST OF INCINERATION FOR RECTANGULAR CONTINUOUS GRATE INCINERATION SYSTEMS

**(1969 dollars)**

Reference Location: Boston, Massachusetts, mid-1969
Plant Capacity: 400 TPD (two, 200-TPD furnaces)
Load Factor: 250 days per year; 3 shifts per day
Annual Consumption: 100,000 tons refuse/year
Capital Investment: $3,100,000

| | Units | Dollars/Unit | Units/Ton Refuse Consumed | Dollars/Ton Refuse Consumed |
|---|---|---|---|---|
| **Variable Costs** | | | | |
| Electricity | kwh | $0.015 | 22.3 | 0.33 |
| Water | M Gal | $0.30 | 0.90 | 0.27 |
| | | | | $0.60 |
| **Semi-Variable Costs** | | | | |
| Labor | | | | |
| 1 crane operator per shift @ $5.00/hour | | | | 0.31 |
| 1 furnace operator per shift @ $5.00/hour | | | | 0.31 |
| 1 charging floor man per shift @ $3.00/hour | | | | 0.19 |
| 2 residue men per shift @ $3.00/hour | | | | 0.38 |
| 1 supervisor @ $14,000/year | | | | 0.14 |
| 1 weigh scale operator @ $5,500/year | | | | 0.06 |
| | | | | $1.39 |
| Overhead @ 40% of labor & supervision | | | | 0.56 |
| Maintenance and repairs @ 2.5% of capital investment annually | | | | 0.78 |
| | | | | $2.73 |
| **Fixed Costs** | | | | |
| Amortization @ 4.9% of capital investment annually | | | | 1.52 |
| Interest on loan @ 3.0% of capital investment annually | | | | 0.93 |
| | | | | $2.45 |
| Total Costs | | | | $5.78 |

## TABLE III–11

## SUMMARY EVALUATION OF INCINERATION CONCEPTS BASED ON EXISTING TECHNOLOGY

| | Criteria Of Performance | | | | | | |
|---|---|---|---|---|---|---|---|
| | Furnace Emissions | | | | | | |
| | Mineral Particulate | Combustibles | Reliability | Residue Quality | Safety | Cost | Potential For By-Product Credits |
| Batch Feed | | | | | | | |
| • Rectangular and Cylindrical | 4 | 1 | 4 | 2 | OK | 4 | – |
| Continuous-Feed | | | | | | | |
| • Rectangular Construction | 3 | 3 | 3 | 3 | OK | 3 | – |
| • Horizontal-Cylindrical Construction | 3 | 3 | 3 | 3 | OK | 3 | – |
| • Ignition Grate plus Burnout Kiln | 2 | 4 | 3 | 4 | OK | 2 | – |
| • Volatilizing Kiln and Burnout Grate Construction | 3 | 3 | 4 | 4 | OK | 2 | – |
| • 3-Stage, Rotary-Kiln Construction | 2 | 3 | 4 | 4 | OK | 2 | – |
| • Waterwall Construction (Grate Burning) | 4 | 4 | 5 | 3 | OK | 2 | Yes |
| • Waterwall Construction (Suspension Burning) | 2 | 5 | 5 | 4 | OK | 2 | Yes |
| Semi-Continuous Feed | | | | | | | |
| • Package System | 3 | 3 | 3 | 3 | OK | 5 | – |
| • Rotary Grate | 2 | 3 | 3 | 3 | OK | 4 | – |
| Continuous Feed with Residue Fusion | 2 | 4 | 3 | 5 | OK | 3 | – |

**Range:** 1 = highly unfavorable; 5 = highly favorable.

In general, the *overall design characteristics* of *most incineration systems support acceptable standards of performance* in all areas, *including air pollution.* The controlling factor, in most cases, is the *unwillingness or* inability of the *municipality to reach the ultimate in every aspect* of incineration performance. Beyond the importance of design suitability, however, the importance of operating practices cannot be discounted. Most incineration systems are quite sensitive to operating variables. In order to meet improved performance goals, the municipality must hire and support men who bring the professionalism and commitment necessary for continued satisfactory operation. A number of plants throughout the country reflect the enthusiastic efforts of such men. Other plants, suffering under the handicaps of inadequate maintenance budgets and intolerable working conditions, neither do, nor could be expected to meet such standards.

*(4) Incineration Concepts Based on Advanced Technology.* Looking to the future, American industry is already well advanced in research and development efforts on advanced concepts for the incineration of solid waste. The Department of Health, Education, and Welfare, in fact, is already evaluating some of the concepts. To date, no major new developments involving the five criteria of performance have come to the fore, since for the most part the advanced concepts basically represent only modified extensions of current practices in incineration or in the pyro-processing and chemical industries. One concept appears especially promising, however. Refuse pyrolysis appears to effect substantial reductions in combustible emissions and flue gas volume. The residue fusion concept, on the other hand, effects the ultimate in refuse volume reduction.

The advanced incineration concepts, briefly described below, have not been developed to the point where they warrant building a full-scale demonstration plant. The present level of development varies from conceptual design to pilot plant studies. The advanced concepts include:

- *Slagging Incinerators* – Involving either combustion of refuse at temperatures above the ash slagging temperature or fusion of the ash as an additional unit operation with more conventional incineration. Supplemental energy sources, which add to operating cost, are used to reach and maintain slagging temperatures in most designs. A summary comparison of techniques now under development is shown in Table III-12. Air pollution problems with these systems are generally equal to or worse than for contemporary plants.

## TABLE III–12

## COMPARISONS OF TOTAL INCINERATION PROCESSES

| | DRAVO/FLK | American Thermogen | Sira | Ferro-Tech | Torrax | Electric Furnace | Oxygen Enrichment |
|---|---|---|---|---|---|---|---|
| Added Capital Cost (per installed ton) over conventional incineration | | ← None to $2000/ton, depending on choice of auxiliary equipment → | | | | | |
| Operating Cost (per ton refuse) over conventional incineration | | ← None to about $2.00/ton (Mostly energy) → | | | | | * |
| Auxiliary Energy Required | Some gas or oil | Coke or gas | Some gas or oil | Coke | Gas | Electric power | Bulk oxygen |
| Air Preheat from Recuperator | Yes | Possible | Yes | Yes | Possible | No | No |
| Potential NOx Air Pollution | High | High | Medium | Medium | High | Lowest | High |
| Relative Size of APC Equipment | Medium | High | Medium | Medium | Medium | Low | Medium |
| Operating Skill Required | Medium to High | High | Medium to High | High | High | Medium to High | High |
| Shredding Required | Yes | No | Yes | No | No | No | No |

* Oxygen required is 0.3 to 0.4 ton/ton refuse, depending on moisture

- *Fluidized Bed Incinerators* – Involving the fluidized bed combustion technique for incineration of solid waste; pretreatment of refuse, such as shredding, metal removal, etc., is generally necessary and feeding problems demand careful attention. Investment and operating costs are high and particulate furnace emissions are enormous. Reductions in combustible and some gaseous pollutant emission is probable.

- *Pyrolysis* – Involving the autogenous thermal decomposition of refuse to produce combustible, organic gases, liquids, and char. The solid waste is thus converted to fuels more susceptible to combustion without substantive air pollution and may be more suitable to combined firing in utility or industrial boilers.

Although these systems are advanced in comparison to alternatives in contemporary incineration systems, and in many cases they require the development of new applied technologies for refuse feeding and handling, all three rest on technology proven in the chemical and metallurgical industries. *From the cost and performance standpoint,* with the exception of special features typically dealing with only one aspect of incinerator performance, they are of no great significance.

From an air pollution standpoint, the concept offering the greatest promise is that of pyrolysis. Figure III-18 is a schematic arrangement of the refuse pyrolysis process, and Table III-13 presents the pyrolysis product yields from different refuse components.

e. Research and Development Needs

The increasing concern for pollution of the environment on the part of the government and its citizenry has become the catalyst in the initiation of a series of research and development programs aimed at identifying, reducing, and eliminating air pollution emissions. The incineration of municipal solid wastes has already been pinpointed as a major contributor to the national air pollution problem by the National Air Pollution Control Administration in its continuing attempts to identify air pollutants, their sources, and effects. In view of the problem, current programs must be expanded and new programs undertaken.

Based on the review of incineration technology presented in this report, an extensive list of research and development programs, focused on the reduction of air pollution from municipal incineration, was compiled (see Chapter VIII-C). The list was based on interview data collected from numerous individuals and companies interested in this problem, and on the ADL study team's review of the state of the art in incinerator technology and air pollution techniques.

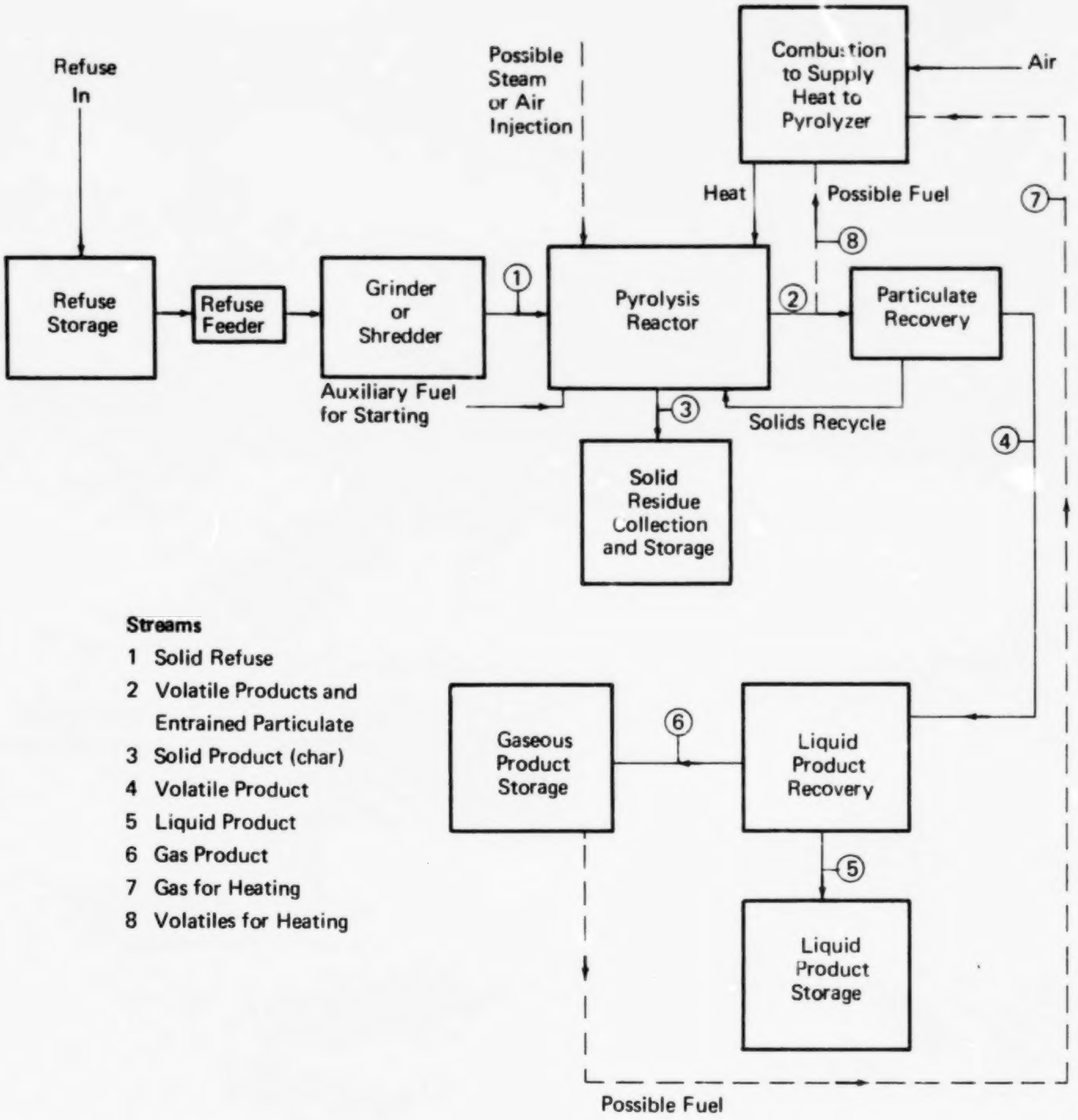

Refuse In
Refuse Storage
Refuse Feeder
Grinder or Shredder
Possible Steam or Air Injection
Combustion to Supply Heat to Pyrolyzer
Air
Heat
Possible Fuel
⑦
⑧
①
Pyrolysis Reactor
②
Particulate Recovery
Auxiliary Fuel for Starting
③
Solids Recycle
④
Solid Residue Collection and Storage
Streams
1 Solid Refuse
2 Volatile Products and Entrained Particulate
3 Solid Product (char)
4 Volatile Product
5 Liquid Product
6 Gas Product
7 Gas for Heating
8 Volatiles for Heating
Gaseous Product Storage
⑥
Liquid Product Recovery
⑤
Liquid Product Storage
Possible Fuel

FIGURE III–18 SCHEMATIC ARRANGEMENT OF REFUSE PYROLYSIS PROCESS

## TABLE III-3

## YIELDS OF PYROLYSIS PRODUCTS FROM DIFFERENT REFUSE COMPONENTS WEIGHT PERCENT OF REFUSE

(from ref. 62)*

| Component | Gas | Water | Other Liquid | Char (ash-free) | Ash |
|---|---|---|---|---|---|
| Cord hardwood | 17.30 | 31.93 | 20.80 | 29.54 | 0.43 |
| Rubber | 17.29 | 3.91 | 42.45 | 27.50 | 8.85 |
| White pine sawdust | 20.41 | 32.78 | 24.50 | 22.17 | 0.14 |
| Balsam spruce | 29.98 | 21.03 | 28.61 | 17.31 | 3.07 |
| Hardwood leaf mixture | 22.29 | 31.87 | 12.27 | 29.75 | 3.82 |
| Newspaper I | 25.82 | 33.92 | 10.15 | 28.68 | 1.43 |
| II | 29.30 | 31.36 | 10.80 | 27.11 | 1.43 |
| Corrugated box paper | 26.32 | 35.93 | 5.79 | 26.90 | 5.06 |
| Brown paper | 20.89 | 43.10 | 2.88 | 32.12 | 1.01 |
| Magazine paper I | 19.53 | 25.94 | 10.84 | 21.22 | 22.47 |
| II | 21.96 | 25.91 | 10.17 | 19.49 | 22.47 |
| Lawn grass | 26.15 | 24.73 | 11.46 | 31.47 | 6.19 |
| Citrus fruit waste | 31.21 | 29.99 | 17.50 | 18.12 | 3.18 |
| Vegetable food waste | 27.55 | 27.15 | 20.24 | 20.17 | 4.89 |
| Mean Values | 24.25 | 23.50 | 22.67 | 24.72 | 11.30 |

*Refuse was shredded, air-dried, and pyrolyzed in a retort at 1500°F.

These programs – all developed in depth relative to objective, description, priority, man/year requirements, and cost – are based on the following problem areas:

- The magnitude and nature of the solid-waste problem as it affects air pollution from incineration;
- The magnitude and nature of the air pollution from incineration;
- The causes of incinerator air pollution;
- Fluidized bed incineration;
- Pyrolysis;
- Slagging incinerators;
- Air pollution control systems.

Based on these major study areas two research programs – one costing $5 million and the other $16 million – were structured. Each is outlined briefly below.

*(1) Research Program – $5 million.* This program consists mainly of high priority study areas (as presented in Chapter VIII). The program would focus on the development of improved incinerator technology, especially to reduce combustible pollutant emission, based on the incorporation of well-proven combustion principles in conventional incineration systems. The study would also attempt to determine the nature and magnitude of air pollution from incineration on a more quantitative basis, with much emphasis placed on the technical and economic aspects of the pyrolysis concept. Table III-14 is a milestone chart of the $5 million program and presents the individual programs selected to comprise the 5-year research and development effort. The program's rate of expenditure is presented in Figure III-19.

*(2) Research Program – $16 million.* The $16 million research program would comprise *all* the research programs outlined in Chapter VIII. The 5-year program would be structured to provide all necessary data and technology to reduce air pollution from incineration to a significant level, all within the constraints of incurred capital and operating expenditures.

Table III-15 is a milestone chart of the $16 million research effort. It lists all programs and their chronological sequence. Figure III-20 presents the program's rate of expenditure.

## B. RECOMMENDATIONS

This report projects the sizable quantities of solid waste that will be generated by our burgeoning population. In view of the imminent problem of disposal, the role of incineration of solid waste, specifically from the viewpoint of improved facilities and techniques, will take on increased importance. Of equal importance will be the controls that must be incorporated in incinerator systems to assure a clean atmosphere for succeeding generations. Chapter VII describes a number of actions, both in terms of equipment modifications and operating practices, that can be taken to reduce air pollution emissions, while moving to the objective of improved techniques for the disposal of solid waste by incineration. In many cases, little added investment is necessary to effect substantial reductions in incineration emissions, since proven incineration practices and equipment already well known to the industry can be incorporated to effect the needed changes.

In view of the reality of these considerations and to highlight this comprehensive study effort, the following recommendations have been made by the study team:

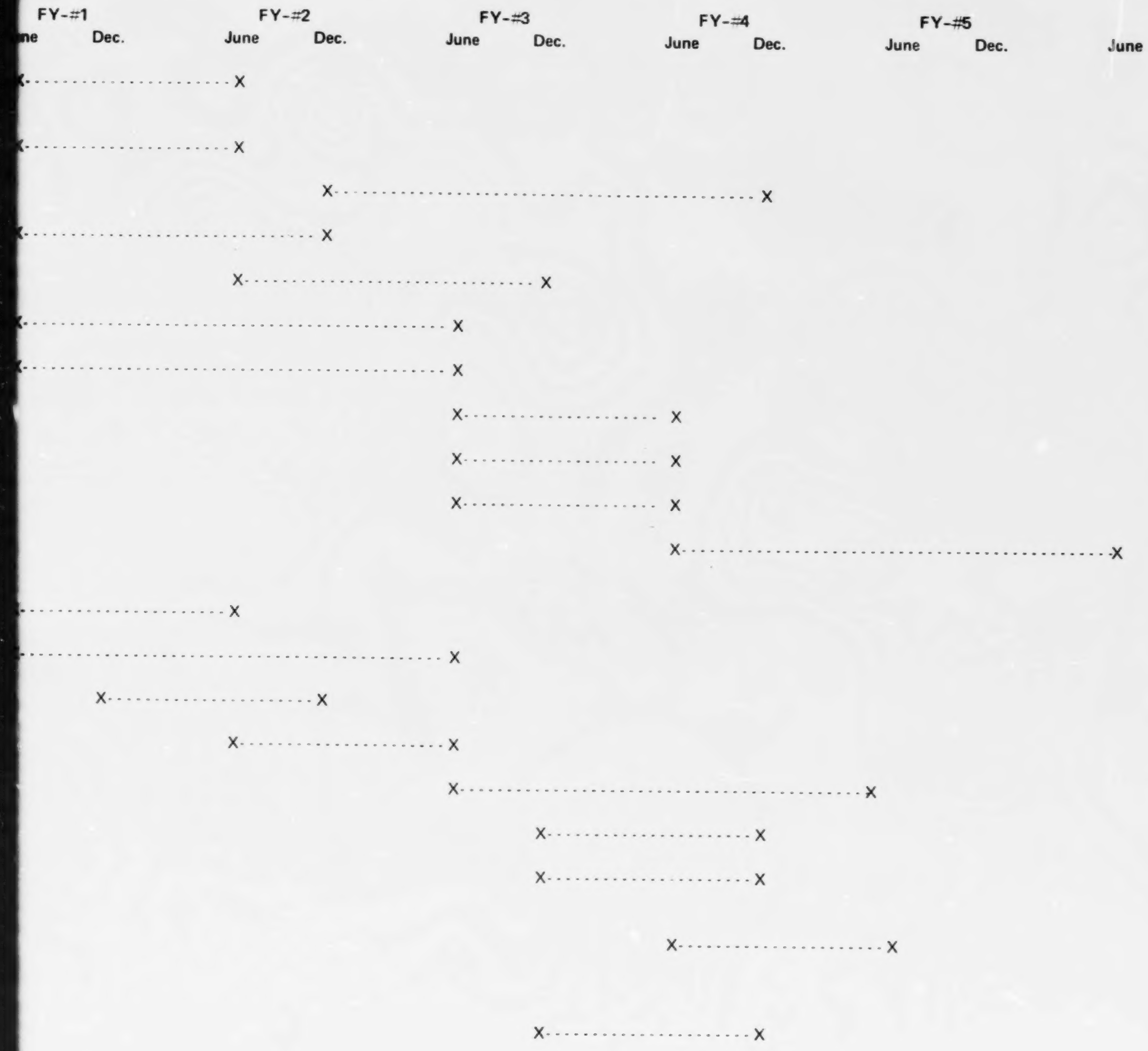
TABLE III–14

MILESTONE CHART FOR 5-YEAR, $5-MILLION RESEARCH

| | R&D Programs | Cost ($000) | FY-#1 June | FY-#1 Dec. | FY-#2 June | FY-#2 Dec. |
|---|---|---|---|---|---|---|
| D-6 | Forecast of Disposal Trends | $ 70 | X- - - - - - | - - - - - - - - - - - | X | |
| E-1 | Test Method Development | 150 | X- - - - - - | - - - - - - - - - - - | X | |
| E-2 | Incinerator Testing | 600 | | | | X- - - - - - - - - |
| F-1 | Pilot Incinerator Design | 150 | X- - - - - - | - - - - - - - - - - - | - - - - - - - - - - - | X |
| F-2 | Pilot Facility Construction | 1,250 | | | X- - - - - - - - - - | - - - - - - - - - - - |
| F-3 | Fundamental Refuse Combustion Study | 150 | X- - - - - - | - - - - - - - - - - - | - - - - - - - - - - - | - - - - - - - - - - - |
| F-4 | Fundamental Mixing Study | 200 | X- - - - - - | - - - - - - - - - - - | - - - - - - - - - - - | - - - - - - - - - - - |
| F-5 | Combustion Study, Pilot-Scale | 150 | | | | |
| F-6 | Mixing Study, Pilot-Scale | 150 | | | | |
| F-7 | Particulate Study-Pilot-Scale | 75 | | | | |
| F-12 | Overfire Combustion Study, Full-Scale | 450 | | | | |
| G-5 | Fluid Bed Economics | 50 | X- - - - - - | - - - - - - - - - - - | X | |
| H-1 | Basic Pyrolytic Studies | 150 | X- - - - - - | - - - - - - - - - - - | - - - - - - - - - - - | - - - - - - - - - - - |
| H-2 | Pilot Pyrolytic System Design | 125 | | X- - - - - - | - - - - - - - - - - - | X |
| H-3 | Pyrolytic Pilot Unit Construction | 475 | | | X- - - - - - - - - - | - - - - - - - - - - - |
| H-4 | Pyrolytic Feed Preparation-Pilot-Scale | 375 | | | | |
| H-6 | Pyrolytic Product Uses | 100 | | | | |
| H-7 | Pyrolytic Air Pollution Evaluation | 100 | | | | |
| H-8 | Economics of Pyrolysis Incineration | 50 | | | | |
| J-1 | APC System Evaluation | 200 | | | | |

## TABLE III–14

## CH E CHART FOR 5-YEAR, $5-MILLION RESEARCH AND DEVELOPMENT PROGRAM



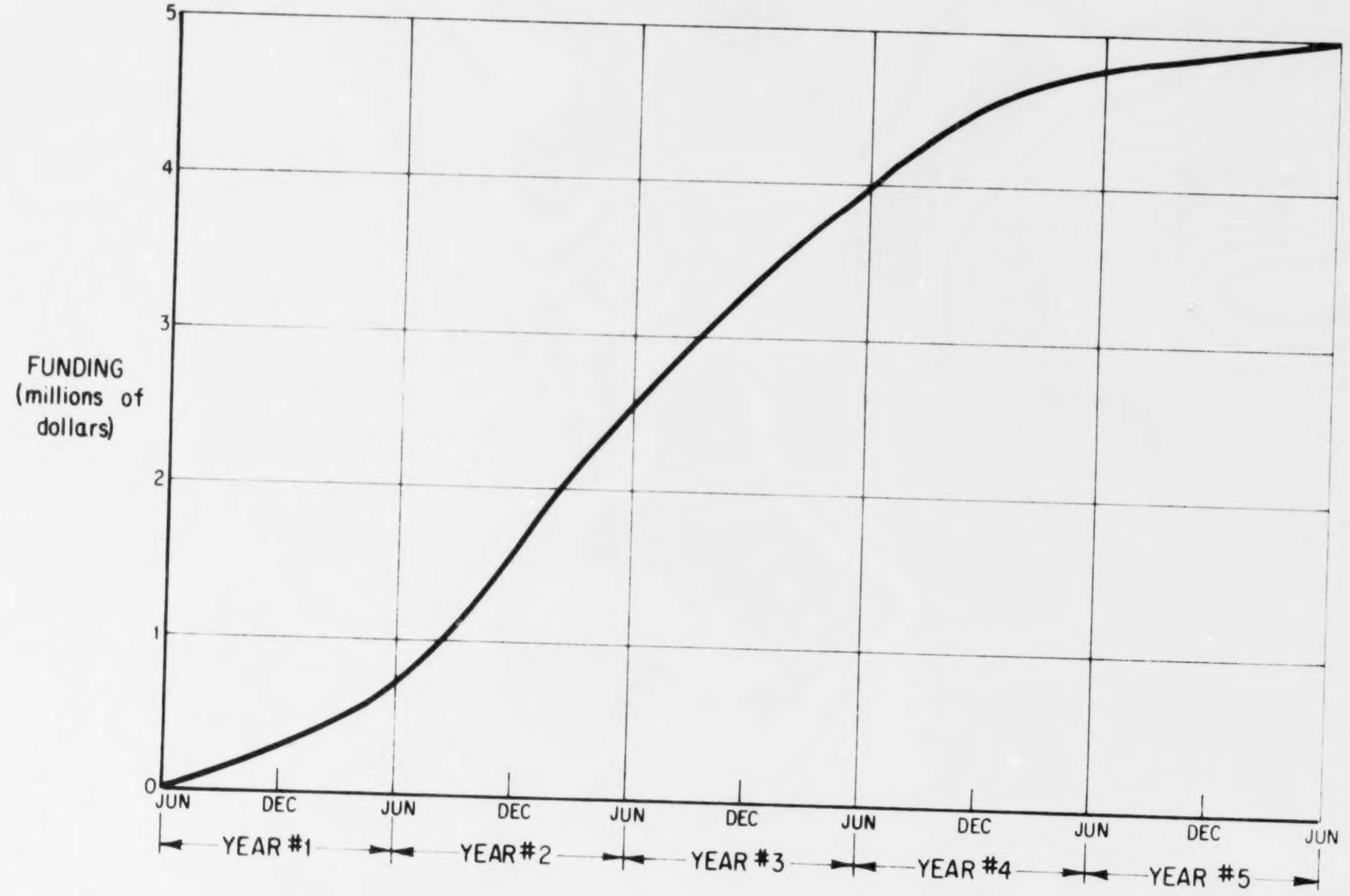


FIGURE III–19 FIVE YEAR – 5 MILLION DOLLAR RESEARCH AND DEVELOPMENT PROGRAM – RATE OF EXPENDITURE GRAPH

TABLE III–15

## MILESTONE CHART FOR $16 MILLION RESEARCH AND

| | R&D Programs | Cost ($000) | FY-#1 June | FY-#1 Dec. | FY-#2 June | FY-#2 Dec. |
|---|---|---|---|---|---|---|
| D-1 | Mobile Laboratory | $ 350 | X- - - | - - - | - - - | - - - X |
| D-2 | Refuse Properties | 750 | | | | X- - - |
| D-3 | Refuse Composition Forecasts | 50 | | | | |
| D-4 | Gaseous Pollutant Emission Forecasts | 50 | | | X- - - | - - - |
| D-5 | Refuse Heat Content Control | 100 | X- - - | - - - | - - - X | |
| D-6 | Forecast of Disposal Trends | 70 | X- - - | - - - | - - - X | |
| E-1 | Test Method Development | 150 | X- - - | - - - | - - - X | |
| E-2 | Incinerator Testing | 600 | | | X- - - | - - - |
| E-3 | Particulate Size Distributions | 200 | | | X- - - | - - - |
| E-4 | Total Incinerator Pollution Forecasts | 50 | | X- - - | - - - | - - - X |
| F-1 | Pilot Incinerator Design | 150 | X- - - | - - - | - - - | - - - X |
| F-2 | Pilot Facility Construction | 1,250 | | X- - - | - - - | - - - |
| F-3 | Fundamental Refuse Combustion Study | 150 | X- - - | - - - | - - - | - - - |
| F-4 | Fundamental Mixing Study | 200 | X- - - | - - - | - - - | - - - |
| F-5 | Combustion Study, Pilot-Scale | 150 | | | | |
| F-6 | Mixing Study, Pilot-Scale | $ 150 | | | | |
| F-7 | Particulate Study – Pilot-Scale | 75 | | | | |
| F-8 | Suspension Burning Studies, Pilot-Scale | 225 | | | | |
| F-9 | $NO_x$ Studies, Pilot-Scale | 75 | | | | |
| F-10 | Combustible Particulate Studies | 150 | | | | |
| F-11 | Bed Combustion Study, Full-Scale | 450 | | | | |
| F-12 | Overfire Combustion Study, Full-Scale | 450 | | | | |
| F-13 | Particulate Study, Full-Scale | 250 | | | | |
| F-14 | $NO_x$ Study, Full-Scale | 100 | | | | |

## EVELOPMENT PROGRAM

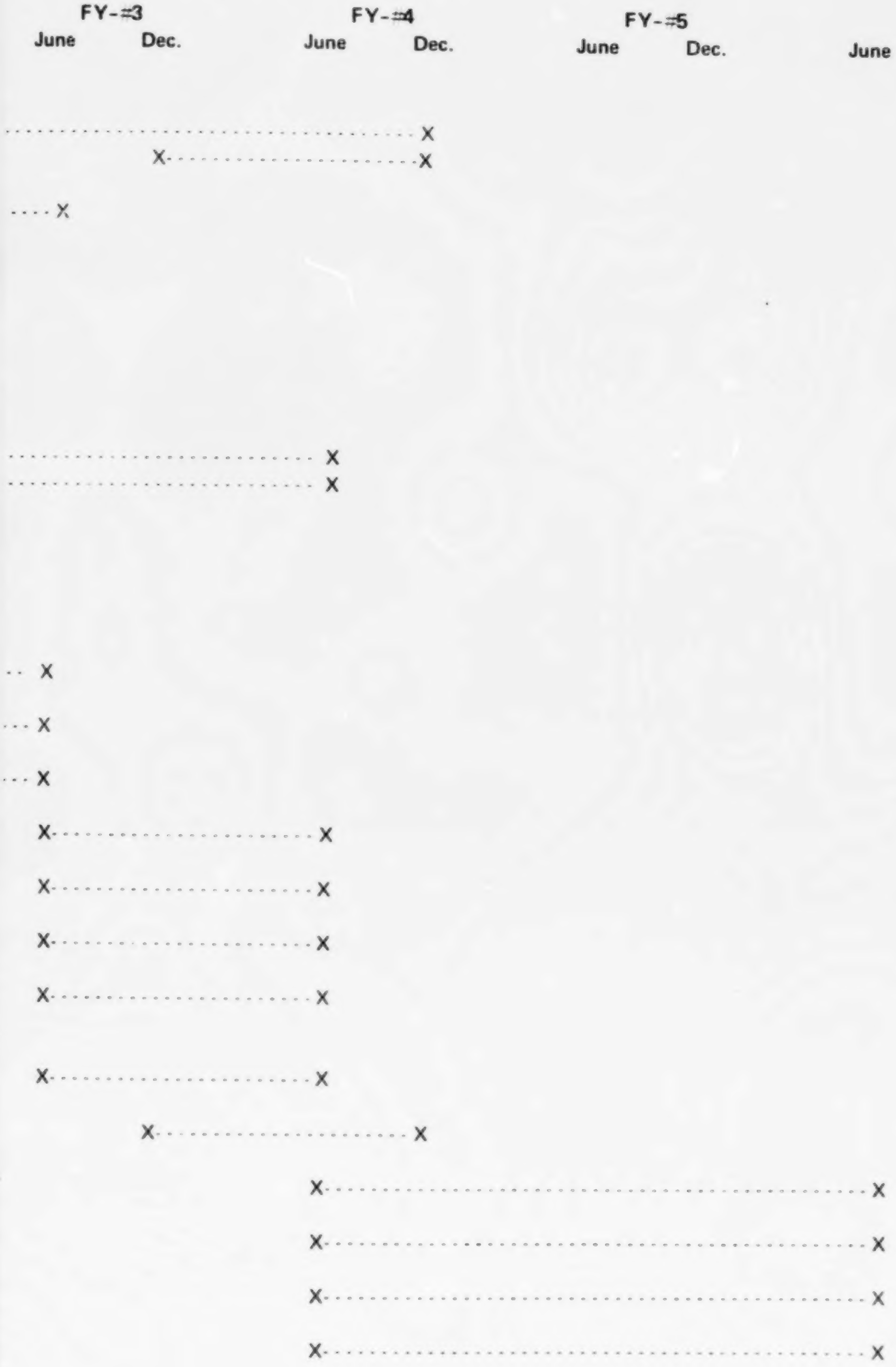


**TABLE III–15 (Continued)**

| | R&D Programs | Cost ($000) | FY-#1 June | FY-#1 Dec. | FY-#2 June | FY-#2 Dec. |
|---|---|---|---|---|---|---|
| G-1 | Pilot Fluid Bed Construction | $ 225 | X- - - - - - - - | - - - - - - - - - - | - - - - - - - - - - | X |
| G-2 | Fluid Bed Feeding Concepts | 550 | | | X- - - - - - - - - - | - - - - - - - - - - |
| G-3 | Fluid Bed Additive Study | 100 | | | | X- - - - - - - - |
| G-4 | Fluid Bed Combustion Study | 100 | | | | X- - - - - - - - |
| G-5 | Fluid Bed Economics | 50 | X- - - - - - - - | - - - - - - - - - - | X | |
| G-6 | Prototype Fluid Bed Design | 250 | | | | |
| G-7 | Prototype Fluid Bed Construction | 2,000 | | | | |
| G-8 | Prototype Fluid Bed Study | 550 | | | | |
| H-1 | Basic pyrolytic Studies | 150 | X- - - - - - - - | - - - - - - - - - - | - - - - - - - - - - | - - - - - - - - - - |
| H-2 | Pilot Pyrolytic System Design | 125 | X- - - - - - - - | - - - - - - - - - - | X | |
| H-3 | Pyrolytic Pilot Unit Construction | 475 | | X- - - - - - - - | - - - - - - - - - - | X |
| H-4 | Pyrolytic Feed Preparation, Pilot-Scale | 375 | | | X- - - - - - - - - - | - - - - - - - - - - |
| H-5 | Pyrolysis Product Control Study | 175 | | | | |
| H-6 | Pyrolysis Product Uses | 100 | | | | |
| H-7 | Pyrolysis Air Pollution Evaluation | 100 | | | | |
| H-8 | Economics of Pyrolysis Incineration | 50 | | X- - - - - - - - | - - - - - - - - - - | X |
| H-9 | Full-Scale Pyrolysis System Design | 300 | | | | |
| H-10 | Full-Scale Pyrolysis System Construction | 2,000 | | | | |
| H-11 | Full-Scale Pyrolysis Study | 750 | | | | |
| I-1 | Refuse Slag Effects | 100 | X- - - - - - - - | - - - - - - - - - - | X | |
| I-2 | Slag Fluidity | 100 | X- - - - - - - - | - - - - - - - - - - | X | |
| J-1 | APC System Evaluation | 200 | | | | |
| J-2 | Fly Ash Handling | 75 | | | | |
| J-3 | Scrubber Water Treatment | 100 | | | | |

```
              FY-#3                        FY-#4                        FY #5
         June       Dec.              June        Dec.             June        Dec                June

     .............................................................. X
     ................X
     ................X

          X............................X
                      X............................X
                                                   X...............................................X

     ...  X



     .................................X

          X............................X
          X............................X
          X............................X

                      X...........................X
                                       X...........................X
                                       X..........................................................X



                     X............................X

                     X............................X
                     X............................X
```

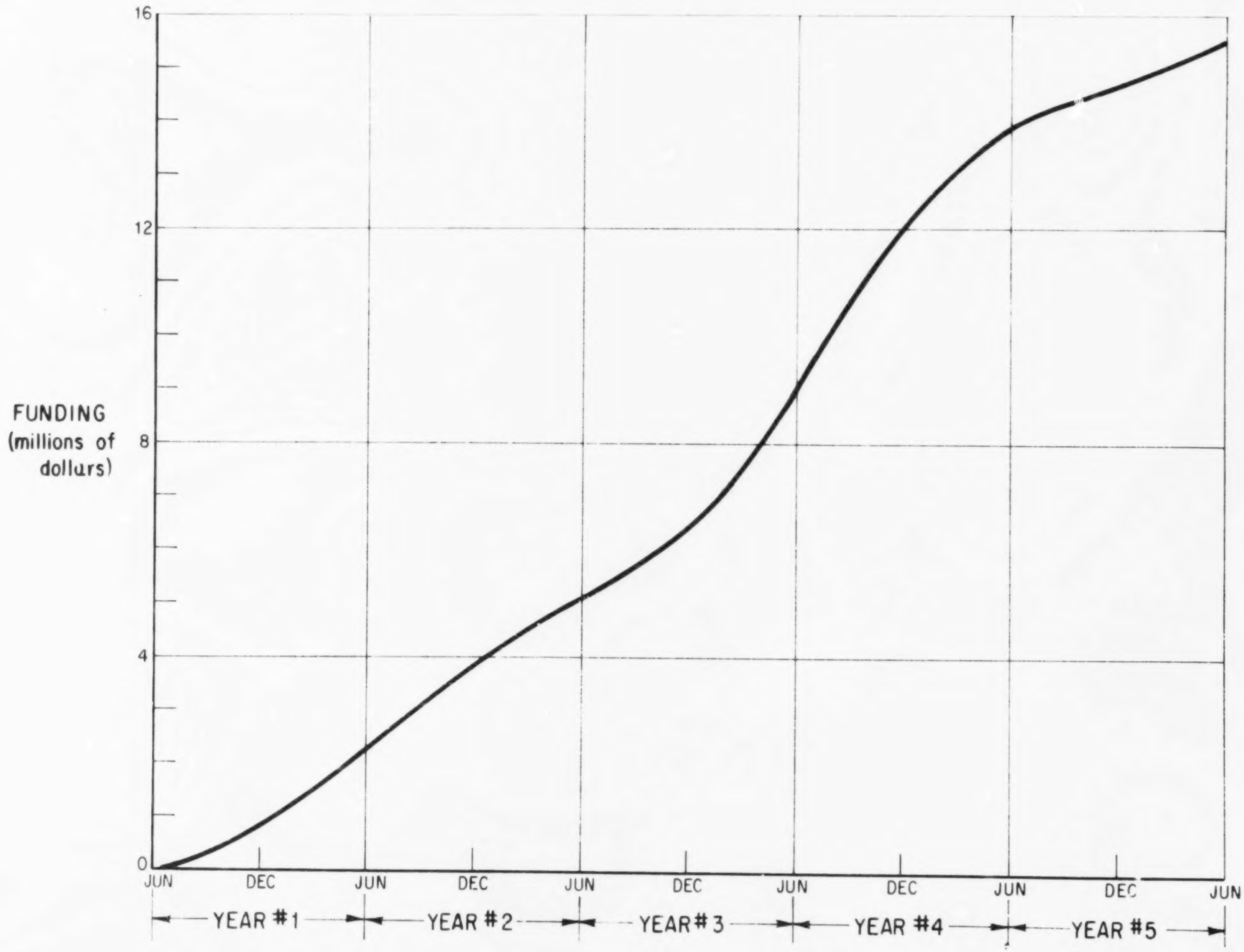


FIGURE III -20 FIVE YEAR – $16 MILLION RESEARCH PLAN – RATE OF EXPENDITURE GRAPH

- The need for improved air pollution performance for incinerators should not be viewed as the province of any one group nor as an independent area for study. Cooperation, cost sharing, joint funding, and other collective means should be exploited through all levels of the public and private sectors to encourage and hasten the development and implementation of low-pollution incinerator systems.
- Because a mere 5 to 8% cost factor differentiates incinerator systems with token APC devices compared from those with a first-class APC system, additional funding to meet the latter objective should be seriously considered by agencies now contemplating construction of new facilities.
- Since the particulate control efficiency (52% average) of the APC systems of plants built in the 1963-1968 period will not be acceptable in the future, the APC performance targets for new plants must be raised to reverse current air pollution trends. A control level of 90% would essentially curtail the rapid increase in total emission in spite of the anticipated four-fold increase in the quantity of refuse incinerated. If the effluent quality of existing plants is improved simultaneously, the total annual particulate emission rate could approach a minimum value by the year 2000. This goal should be sought.
- Federal and state sponsorship of programs to demonstrate the performance advantages and possibilities of air pollution control based on new concepts and techniques should be encouraged.
- In view of the economics of building new plants and modifying facilities, municipalities should institute pilot study groups to weigh the advantages of pooling resources and facilities as a long-range objective of creating an efficient, modern incineration system for the disposal of solid waste.
- Better mixing techniques must be adopted and incorporated in incinerator systems to reduce or eliminate combustible pollutant emission.

- Undergrate air flow should be reduced to the lowest levels possible and controlled to lessen particulate liftoff consistent with burning rate and grate protection considerations.

- More training of incinerator operators should be introduced, not just to teach them how to operate the facility, but to orient them in basic incineration technology.

- In view of the proven efficiency of filter bags as APC devices, more advanced experimentation and testing should be considered.

- Advanced technology concepts should be given due consideration. Of the three described in this report – slagging, fluidized bed, and pyrolysis – the latter deserves prompt attention because it can effect substantial reductions in combustible emissions and flue gas volume.

- In view of projected increases in hydrogen chloride emissions from incinerators, consideration should be given by both private and public sectors to seek methods to minimize increases in the use of halogenated polymeric materials.

# IV. THE SOLID WASTE PROBLEM

# IV. THE SOLID WASTE PROBLEM

## A. INTRODUCTION

The present and growing quantity of collected municipal solid waste provides the incentive for expansion of incineration facilities. Also, the changing nature of refuse (composition, heating value, ash content, etc.) has a direct impact on future incinerator design and air pollution problems. As a consequence of the strong influence of refuse quantity and nature on the growth of incineration and potential incinerator air pollution, it is an objective of this study to evaluate these parameters. This portion of the report presents the results of that effort.

The use of incineration to meet waste disposal needs is significantly more common in metropolitan areas where high population density often inhibits landfill and where high total population results in generation of large quantities of refuse material. Although the rural areas in the United States cannot be discounted in assessing the national solid waste problem, the low total population and refuse generation density (pounds per square mile per day) characteristic of rural areas does not, in general, provide the incentive nor the financial resources for incineration facilities. As a result, the refuse burden, population base and other parameters of importance to the growth of incineration are significant only in urban areas. For this reason, urban areas were chosen as represented by the State Economic Areas (SEA's) as defined by the Census Bureau.

The refuse composition dealt with herein deals primarily with the waste which would normally be delivered to an incinerator. It does not, therefore, include agricultural wastes, industrial wastes, automobiles, and large quantities of oversize bulky wastes, such as demolition lumber, tree stumps, household appliances, etc.

This Chapter evaluates present and future composition and quantity of municipal solid waste, to identify a national average, and from this base extends the forecast to a state-by-state basis. The results, properly interpreted, should be useful to many groups working in the field of solid waste and incineration. They do not, however, provide a definitive design basis for municipal planning or for equipment development. Effects such as industrial mix in the community, regulations on open burning, weather conditions, etc., can cause wide variations in refuse composition compared to country-wide trends. The underlying methodology, however, tailored to local realities, is sound and could be adapted to derive more focused forecasts.

## B. THE NATURE OF REFUSE

### 1. Introduction

The quantities of solid waste refuse generated now and in the future and the physical and chemical nature of this waste have significant implications regarding the overall management of solid waste; the numbers and capacities of municipal incinerators to be constructed; and the level and type of resulting air pollution. The changing physical and chemical nature of the refuse will also significantly influence the design and operating parameters of these future facilities as well as modifications to equipment and operating practices for existing incineration plants.

In order, then, to appropriately address these concerns, the present national solid waste load and the nature of refuse were estimated. With these values serving as a base, projection techniques were then developed to predict solid waste loads and the physical and chemical nature of refuse through the year 2000. These predicted values serve as inputs to the computer model described in Section VI which evaluates the air pollution levels.

### 2. Per-Capita Refuse Collection in 1968

The Bureau of Solid Waste Management (BSWM), Department of Health, Education and Welfare, is now conducting a national survey of community solid waste practices.[1] Part of this survey seeks to define the average per-capita collected waste load on a state, regional, and national basis. Detailed questionnaires prepared by BSWM have been returned by communities representing more than 60% of the national population. Based on these results, BSWM has developed preliminary estimates of the per-capita municipal waste load collected in 1968 for the responding states. The collected per-capita refuse is broken down into 11 basic categories:

- Household
- Commercial
- Industrial
- Agricultural
- Institutional
- Demolition and Construction
- Street and Alley
- Tree and Landscaping
- Park and Beach
- Catch Basin
- Sewage Solids

In general, household and commercial refuse comprises the major portion of the waste burned in municipal incinerators. In some instances, communities participating in the BSWM survey reported abnormally high values for the weight of municipal waste collected. It was the conclusion of BSWM that these high values included significant quantities of refuse delivered to private, industrial and agricultural disposal facilities. As this study is concerned only with municipal refuse, it was decided to exclude those data felt to reflect industrial and agricultural contributions.

Both an urban and rural breakdown of per-capita household-commercial municipal refuse collected in 1968 for each of the states from which data have been received are presented later in this chapter.*[2] It should be emphasized that at this time BSWM does not consider some of these data as reliable and, in many instances, they report the data as poor. This information, however, represents the best available data on average per-capita refuse rates. As new and more accurate data become available, these numbers can be updated.

The data shown represent state-wide averages, and thus these data should not be used to estimate the waste load in any localized region without consideration of the local commercial, residential, and industrial mix and the practice of nonmunicipal disposal.

### 3. National Average Composition of Municipal Refuse – 1968

Data on the composition of municipal refuse throughout the United States are limited. A research of available information sources, including demonstration, research and planning grants, and data directly generated by the BSWM have thus far uncovered only 23 useful, apparently independent data sets. In general, these data were generated by methodical sampling, segregation and weighing of municipal refuse samples taken throughout the United States. These data reflect refuse compositions similar to that of refuse charged into incinerators (i.e., on an "as-fired" basis). In a subsequent portion of the section, it will be useful to shift to an "as-discarded" basis. The difference between these bases arises from the exchange of moisture between refuse categories after mixing has taken place in refuse collection cans, etc. In this moisture exchange process, high moisture refuse components (e.g., food waste) lose moisture, and low moisture components (e.g., paper and rags) gain moisture. After such a process, the aggregate composition has not changed, but the weight distribution among the various refuse categories is different.

Table IV-1 shows these data together with the areas from which the data were taken. The 10 categories into which the refuse has been divided are for the most part self-explanatory. "Textiles" includes both natural and synthetic woven fibers and spun-bonded synthetics. Synthetic nonwovens, such as PVC coatings used in clothing and apparel, are included under the "Plastics" category. "Yard Wastes" comprise such items as leaves, grass, plants, and trimmings. Some dirt is associated with yard wastes. The "Miscellaneous" category is comprised primarily of bricks, rocks, and dirt (demolition waste, street sweepings, etc.).

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* Table IV-15.

## TABLE IV–1

## REFUSE COMPOSITION DATA
(weight percent on an as-fired basis)

| Location | Notes | Food Wastes | Yard Wastes | Misc | Glass and Ceramics | Metal | Paper Product | Plastics | Leather and Rubber | Textiles | Wood | Oil, Paint, Chemicals, etc | Total | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 City, New Jersey Region | Average for Paterson, Clifton, Passaic, Wayne | 8.3 | 13.3 | 8.96 | 6.44 | 9.44 | 43.87 | 2.66 |  | 4.52 | 2.96 |  | 100.49 | 4 |
| Composite | As collected, includes 9.05% adjusted moisture | 8.40 | 6.88 | 10.01 |  | 6.85 | 52.70 | 1.52 | 0.76 | 0.76 | 2.29 | 0.76 | 99.98 | 5 |
| Hempstead, Long Island, N.Y. | Predominantly residential | 10.9 | 17.6* |  | 9.6 | 8.5 | 42.6 | 4.6 |  | 3.1 | 3.2 |  |  | 6 |
| Hempstead, Long Island, N.Y. | Including residential and commercial; excluding bulky and industrial | 12.0 | 20 |  | 8 |  | 46.0 | 4 |  | 3.0 | 7.0 |  | 100.0 | 7 |
| Johnson City, Tennessee | Residential, 10/67 | 26.1 | 1.6 | 1.0 | 11.0 | 10.9 | 45.0 | 1.7 | 1.0 | 1.4 | 0.4 |  | 100.01 | 2 |
| Johnson City, Tennessee | Municipal, 7/68 | 34.6 | 2.3 | 0.2 | 9.0 | 10.4 | 34.9 | 3.4 | 2.4 | 2.0 | 0.8 |  | 100.0 | 2 |
| Weber County, Utah | Residential and Commercial, 4/68 | 8.5 | 4.2 | 5.9 | 4.6 | 8.4 | 61.8 | 2.5 |  | 2.0 | 2.2 |  | 100.1 | 2 |
| Cincinnati, Ohio | Residential, 10/66 | 28.0 | 6.4 | – | 7.5 | 8.7 | 42.0 | 1.6 | 1.0 | 1.4 | 2.7 |  | 99.3 | 8 |
| Memphis, Tennessee | Residential, 7/68 | 19.7 | 12.1 | 12.5 | 9.8 | 6.6 | 29.8 | 3.0 |  | 4.8 | 1.7 |  | 100.0 | 2 |
| Alexandria, Virginia | Residential and Commercial, 5/68 | 7.5 | 9.5 | 3.4 | 7.5 | 8.2 | 55.3 | 3.1 |  | 3.7 | 1.7 |  | 99.9 | 2 |
| San Diego, California | Residential and Commercial, 1967 | 0.8 | 21.1 | – | 8.3 | 7.7 | 46.1 | 0.3 | 4.7 | 3.5 | 7.5 |  | 100.0 | 9 |
| Genesee County, Michigan | Includes commercial, industrial, domestic, and demolition wastes | 7.11 | 1.99 | 23.62 | 3.34 | 4.64 | 20.39 | 1.49 |  | 3.01 | 22.41 | 12.00 | 100.0 | 10 |

*Average of four tests:

| Date | % Yard Wastes |
|---|---|
| 6/1/66 | 33.3 |
| 6/23/66 | 19.0 |
| 2/21/67 | 0.3 |
| 4/3/67 | 17.9 |

## TABLE IV–1 (Continued)

| Location | Notes | Food Wastes | Yard Wastes | Misc. | Glass and Ceramics | Metal | Paper Product | Plastics | Leather and Rubber | Textiles | Wood | Oil, Paint, Chemicals, etc | Total | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Flint, Michigan | Annual Average | 32.6 | 13.5 | 0.3 | 17.9 | 14.5 | 17.5 | 2.3 | | 0.5 | 0.9 | | 100.0 | 10 |
| Genesee County, Michigan | Domestic | 26.0 | 10.8 | 0.2 | 14.3 | 11.8 | 34.0 | 1.8 | | 0.4 | 0.7 | | 100.0 | 11 |
| Santa Clara, California | | 2.3 | 23.8 | | 12.[illegible] | 7.6 | 47.5 | 1.0 | 1 (est.) | 1.2 | 1 (est.) | | 98.1 | 12 |
| Philadelphia, Pennsylvania | Includes significant quantities of industrial wastes | 5.0 | 16.4 | | 9.1 | 8.4 | 54.4 | 0.2 | 1.5 | 2.6 | 2.4 | | 100.0 | 13 |
| Jefferson County, Kentucky | As collected, Residential, Average 66/67 | 19.8 | | 1.3 | 10.5 | 9.3 | 59.1 | | | | | | 100.0 | 14 |
| New Jersey | | 10.0 | | | 4.0 | 8.0 | 51.0 | 4.0 | | | 4.0 | | 81.0 | 15 |
| Ohio | | 28.0 | | | 8.0 | 9.0 | 42.0 | 3.0 | | | 3.0 | | 93.0 | 15 |
| Arizona | | 22.0 | | | 8.0 | 10.0 | 43.0 | 1.0 | | | 2.0 | | 86.0 | 15 |
| California | | 15.0 | | | 2.0 | 7.0 | 54.0 | 2.0 | | | 2.0 | | 82.0 | 15 |
| Tennessee | | 26.0 | | | 11.0 | 11.0 | 46.0 | 5.0 | | | 0.3 | | 99.3 | 15 |
| Generalized Analysis | From study made by Purdue University | 12.0 | 12.0 | 14.5 | 6.0 | 8.0 | 42.0 | 0.7 | 1.0 | 0.6 | 2.4 | 0.8 | 100.0 | 16 |
| Hamilton, Ontario Canada | [illegible] 28-July 26, 1968 | 31.0 | 13.0 | | 7.0 | 5.0 | 33.0 | 1.3 | 1.0 | 2.0 | 6.0 | | 99.0 | 17 |

An examination of these data shows a wide variation in reported composition. Review and analysis of these data indicate two refuse categories which are highly dependent on local conditions. The fraction of "Yard Waste" appears very sensitive to both geographical location and the season of the year when the sample was taken. The "Miscellaneous" fraction is dependent upon local practices and regulations as regards the collection of demolition and other such wastes. The other eight categories appear to be much less subject to seasonal and geographical variation.

Based on these observations, the data from these 23 sources were modified to reflect an average composition of municipal waste with the "Yard Wastes" and "Miscellaneous" materials removed. Table IV-2 shows the results.

### TABLE IV-2

### ESTIMATED ANNUAL AVERAGE NATIONAL REFUSE COMPOSITION

**(On a Yard Waste-Free and Miscellaneous-Free As-Fired Basis)**

| Component | Mean Weight Percent |
|---|---|
| Glass | 9.9% |
| Metal | 10.2 |
| Paper | 51.6 |
| Plastics | 1.4 |
| Leather and Rubber | 1.9 |
| Textiles | 2.7 |
| Wood | 3.0 |
| Food Wastes | 19.3 |
|  | 100.0 |

A statistical analysis of these reduced data was made to evaluate the significance of these mean refuse values. Table IV-3 shows the results of this analysis. The fourth column lists the mean weight percent of each of the eight refuse components being considered. Column 6 indicates the 95% confidence limits about the mean for each of these refuse categories. The values of Column 7 show the 95% confidence range for the weight percent of each of the municipal refuse components on a yard waste and miscellaneous-free basis.

The relatively small 95% confidence limits in Column 6 indicate that the limited data available yield a usable estimate of "average U.S. refuse." The 95% confidence limits for metal and paper vary by less than or equal to 10% of their mean values. The 95% confidence limits for glass is less than 20% of its mean. The confidence limits for plastics, leather, and rubber relative to their mean values are high; 52.8% and 65.8% of their means, respectively. However, the 95% confidence range for both these components is only 1-3%.

The averages and confidence ranges of the refuse components expressed in Table IV-3 should be considered as estimates of the composition of average national refuse (on a yard waste and miscellaneous-free basis) based on the limited quantity of available data. As more refuse analyses are performed and more data become available, significant improvements on the reliability and precision of the data can be attained.

In order to further describe refuse composition, it is necessary to obtain an estimate of the weight-percent of the "Miscellaneous" category in municipal refuse. The weight fractions of this material can be expected to be highly variable as each municipality may have significant variations in the quantities of this refuse type which is collected and the quantities and nature of this collected refuse ultimately disposed of at incinerator facilities versus landfill or other disposal methods. Data from Table IV-1 on the composition of municipal refuse show variations in the weight-percent of "Miscellaneous" material from 0 to 16%. Table IV-4 shows the weight-percent of "Miscellaneous" in these refuse samples along with the percent "Yard Wastes" for that sample. In order to eliminate the seasonal dilution effect of "Yard Wastes" on the percent "Miscellaneous," the "Miscellaneous" category in Table IV-1 was expressed on a "Yard Waste-free" basis. The results are shown in Table IV-4.

Eleven of the 15 samples in Table IV-4 contain less than 6% miscellaneous refuse. Each of the other four samples contains 9% or more miscellaneous refuse. In our judgment, weight-percents of "Miscellaneous" material larger than 8 or 9% in municipal refuse appear unusual and probably reflect unique local conditions not applicable on a national basis. The average weight-percent of "Miscellaneous" refuse (on a Yard Waste-free basis) was, therefore, based only on the first 11 values.

With the values of the weight-percent of "Miscellaneous" refuse on a Yard Waste-free basis estimated at 1.7%, the estimated average composition of municipal refuse on a Yard Waste-free basis was developed utilizing the data in Table IV-3. Table IV-5 illustrates the resulting values.

### 4. Average Annual Composition of Municipal Refuse Reflecting the Effects of Climate

In order to estimate the average composition of municipal refuse for individual states, it is necessary to estimate for each state the average annual weight-percent of yard wastes. The average national composition in Table IV-5 can then be readjusted for each state to include the appropriate weight-percent of this component.

## TABLE IV-3

## ESTIMATE OF THE NATIONAL ANNUAL AVERAGE COMPOSITION OF MUNICIPAL REFUSE EXCLUDING YARD WASTES AND MISCELLANEOUS CATEGORIES

(as-fired basis)

| (1) Component | (2) Data* Samples Utilized | (3) Mean Weight Percent | (4) % Mean (100% basis) | (5) Estimated Standard Deviation S(X) | (6) 95% Confidence Limits | (7) 95% Confidence Range |
|---|---|---|---|---|---|---|
| Glass | 23 | 9.7 | 9.9 | 4.37 | 1.89 | 8.0-11.8 |
| Metal | 23 | 10.0 | 10.2 | 2.18 | .93 | 9.3-11.1 |
| Paper | 23 | 50.3 | 51.6 | 11.67 | 5.04 | 46.6-56.6 |
| Plastics | 9 | 1.4 | 1.4 | .96 | .74 | 0.7-2.1 |
| Leather & Rubber | 9 | 1.9 | 1.9 | 1.62 | 1.25 | 0.7-3.2 |
| Textiles | 17 | 2.6 | 2.7 | 1.80 | .93 | 1.8-3.6 |
| Wood | 22 | 2.9 | 3.0 | 2.39 | 1.06 | 1.9-4.1 |
| Food Wastes | 23 | 18.8 | 19.3 | 10.95 | 4.73 | 14.6-24.0 |
| | | 97.6 | | | | |

---

*Several data sets were not presented in a form suitable for extracting the weight fractions of all of the above refuse components.

## TABLE IV-4

## DATA FOR PERCENT "MISCELLANEOUS" IN MUNICIPAL REFUSE
(as-fired basis)

| Weight-Percent "Miscellaneous" | Weight-Percent Yard Waste | Percent "Miscellaneous" (yard waste-free basis) | |
|---|---|---|---|
| 0.0 | 21.1 | 0.0 | Avg. 1.7% |
| .2 | 10.8 | 0.2 | |
| .2 | 2.3 | 0.2 | |
| .3 | 13.5 | 0.3 | |
| .7* | 6.4 | 0.7 | |
| 1.0* | 1.6 | 1.0 | |
| 1.0* | 13.0 | 1.1 | |
| 1.3 | 0.0* | 1.3 | |
| 2.0* | 23.8 | 2.6 | |
| 3.4 | 9.5 | 3.8 | |
| 5.9 | 4.2 | 6.2 | |
| 12.5 | 12.1 | | |
| 14.0 | 12.0 | | |
| 16.4 | 0.0* | | |

*Obtained from Table IV-1 by difference.

## TABLE IV-5

## ESTIMATED ANNUAL AVERAGE NATIONAL REFUSE COMPOSITION
(on a yard waste-free as-fired basis)

| Component | Weight Percent |
|---|---|
| Glass | 9.7 |
| Metal | 10.0 |
| Paper | 50.7 |
| Plastics | 1.4 |
| Leather & Rubber | 1.9 |
| Textiles | 2.6 |
| Wood | 2.9 |
| Food Wastes | 19.1 |
| Miscellaneous | 1.7 |
| | 100.0% |

Table IV-6 presents the only seasonal yard waste data available, taken from Table IV-1. Regions in the North and Northeastern United States represent areas which experience wide seasonal variations in climate. Significant quantities of grass, leaves, plants, shrubs, and foliage growth are observed in the refuse of these regions during the growing season and little or none during the winter. In Table IV-6, data on the weight-percent of yard waste in municipal refuse were arranged in appropriate seasonal categories and seasonal averages computed where possible. From this analysis, an annual average, based on these seasonal averages, may be estimated.

For areas experiencing little climate variation, it was assumed that little variation occurs in the percent of yard waste in refuse during the year. For uniform climate areas, only two data points for refuse composition were available, both in Southern California. These two data points were then averaged with the summer values of percent yard waste in the seasonal regions to estimate the annual mean percent of yard waste in refuse for growing season periods.

From these limited data, it was postulated that the average percent yard waste in refuse collected during the growing season was 20.4%. Secondly, it was assumed that the average number of "frost-free days" (a collected statistic)[3] could be used as a measure of the fraction of the year when growing season yard waste rates would be experienced. By this means, the annual average percent yard waste can be estimated for each state using the equation:

$$\text{Percent yard waste} = 20.4\% \left(\frac{\text{frost-free days per year in the state}}{365}\right)$$

(As-Fired Basis)

### 5. Average Refuse Composition

#### a. "As-Discarded" vs. "As-Fired" Refuse Compositions

Discarded solid waste, as it is mixed together with other refuse materials, may either lose or absorb mositure prior to being incinerated. Food wastes, for example, may transfer significant quantities of moisture to paper and textiles. Glass, on the other hand, may not be expected to either transfer or absorb significant quantities of moisture. This moisture transfer phenomenon must be accounted for in projecting the load of individual refuse categories into the future (discussed in the next section).

As an example, paper has been found to contain about 24.3% moisture as fired in an incinerator. When used and manufactured, however, paper contains about 8.0% moisture. Since the projection technique determines the growth of paper waste from the ratio of paper production in the United States over a time

## TABLE IV-6

## DATA FOR WEIGHT PERCENT YARD WASTE IN REFUSE
(as-fired basis)

| Regions | Summer | Spring | Winter | Fall | Season Not Specified |
|---|---|---|---|---|---|
| Seasonal | | | | | 2.0 |
| | 33.3 | 17.9 | .3 | 6.4 | 6.9 |
| | 19.0 | 9.5 | | 1.6 | 13.3 |
| | 13.0 | 4.2 | | | 10.8 |
| | 12.1 | | | | 13.5 |
| Average | 19.4% | 10.5% | < .1% | 4.0% | 9.3% |
| Santa Clara, California | 23.8 | | | | |
| San Diego, California | 21.1 | | | | |
| Average* | 20.4% | | | | |

*Average for six data points.

interval, the proper base number must be the pounds of paper in refuse on the same moisture base as for paper manufacture and use. Otherwise, we would project, in part, the water which has come from other waste categories which do not necessarily increase in quantity at the same rate as does paper. As a consequence, therefore, the "as-fired" compositions previously developed must be converted to an "as-discarded" basis so that the moisture can be weighted with the proper refuse components. Note, however, that this manipulation does not change the *total* moisture content in base year refuse.

Table IV-7 shows our estimates, based on refuse analysis data[5,6] and ADL estimates, of the moisture contained in each refuse category, on "as-discarded" and "as-fired" bases. These moisture contents were utilized to adjust the "as-fired" values to an "as-discarded" basis for use as base refuse compositions in projecting refuse compositions up through the year 2000.

Table IV-8 presents estimated annual average refuse compositions for three geographical areas with varying numbers of frost-free days to illustrate the resulting effect on annual average refuse composition. The composition is on an "as-discarded" basis.

b. Average Refuse Composition

Using the methodology and data above, we have developed a representative municipal refuse composition useful as a reference point for heat balances, material balances, etc. (Table IV-9.) It should always be recognized, however, that whenever derivative quantities (e.g., heat, ash or moisture content) are important to a process, quantitative consideration of the effects of at least ± 25% variations should be made to allow for local conditions.

Table IV-10 represents our estimate of the ultimate analysis of refuse categories (in percent). It was based on available literature,[5,6] published information and ADL estimates of the ultimate analysis of each refuse category *on a dry basis*, together with the percent fixed carbon and heating values.

## TABLE IV–7

## PERCENT MOISTURE IN REFUSE CATEGORIES ON "AS–DISCARDED" AND "AS–FIRED" BASES

| Refuse Category | Percent Moisture<br>"As-Fired" | "As-Discarded" |
|---|---|---|
| Glass | 3.0 | 2.0 |
| Metal | 6.6 | 2.0 |
| Paper | 24.3 | 8.0 |
| Plastics | 13.8 | 2.0 |
| Leather & Rubber | 13.8 | 2.0 |
| Textiles | 23.8 | 10.0 |
| Wood | 15.4 | 15.0 |
| Food Wastes | 63.6 | 70.0 |
| Yard Wastes | 37.9 | 50.0 |
| Miscellaneous | 3.0 | 2.0 |

## TABLE IV–8

## ESTIMATED ANNUAL AVERAGE OF MUNICIPAL REFUSE COMPOSITION (1968)

("As-Discarded" Basis)

| Category | Un-Seasonal State (e.g., Florida) | Semi-Seasonal State (e.g., Alabama) | Seasonal State (e.g., Massachusetts) |
|---|---|---|---|
| Glass | 7.6 | 8.1 | 8.8 |
| Metal | 7.5 | 8.1 | 8.7 |
| Paper | 32.6 | 35.1 | 38.2 |
| Plastics | 1.0 | 1.1 | 1.1 |
| Leather & Rubber | 1.3 | 1.4 | 1.5 |
| Textiles | 1.8 | 1.9 | 2.0 |
| Wood | 2.3 | 2.4 | 2.7 |
| Food Wastes | 18.2 | 19.5 | 21.1 |
| Yard Wastes | 26.1 | 20.7 | 14.1 |
| Miscellaneous | 1.6 | 1.7 | 1.8 |

## TABLE IV-9

## AVERAGE REFUSE COMPOSITION – AS-DISCARDED BASIS

| Category | Wt % | Description |
|---|---|---|
| Glass | 8.3% | Bottles (primarily) |
| Metal | 8.2 | Cans, Wire, Foil |
| Paper | 35.6 | Various Types, Some with Fillers |
| Plastics | 1.1 | Polyvinyl Chloride, Polyethylene, Styrene, etc. as Found in Packaging, Housewares, Furniture, Toys and Nonwoven Synthetics |
| Leather & Rubber | 1.5 | Shoes, Tires, Toys, etc. |
| Textiles | 1.9 | Cellulosic, Protein, and Woven Synthetics |
| Wood | 2.5 | Wooden Packaging, Furniture, Logs, Twigs |
| Food Wastes | 23.7 | Garbage |
| Miscellaneous | 1.7 | Inorganic Ash, Stones, Dust |
| Yard Wastes | 15.5 | Grass, Brush, Shrub Trimmings |
|  | 100.0% |  |

The data below present the overall refuse characteristics in 1968 for refuse containing a yard waste fraction of 15.5% on an as-discarded basis (12.6% on an as-fired basis). A more complete presentation of the combustion characteristics of average refuse is presented in Appendix C.

**Overall Refuse Characteristics – Average 1968 Refuse**

Heating Value: 4450 Btu/lb as fired (HHV)
% Moisture: 28.16%
% Ash: 20.8%
Air Requirement: 3.21 pounds/pound refuse (stoichiometric)
M Btu (HHV) per Pound of Stoichiometric Air: 1.39

## C. REFUSE PROJECTIONS

The preceding analysis provides a reference point from which to forecast the changing nature and relative quantity of solid waste in the future. As in any extrapolation, the base year data point has a great influence upon the terminus, in this case, the year 2000. It is anticipated that the significant increase in federal, state, and municipal interest in solid waste will greatly improve upon the data base which supports such projections. As a consequence, the following paragraphs address, in considerable detail, the methodology of projection. As new data become available, the methodology can be readily applied and improved projections prepared.

## TABLE IV–10

## ESTIMATED ULTIMATE ANALYSIS OF REFUSE CATEGORIES (%) (DRY BASIS)

| Category | C | H | O | N | Ash | S | Fe | Al | Cu | Zn | Pb | Sn | P** | $Cl^-$ | Se | % Fixed Carbon (Dry Basis) | Heating Value (Btu/lb) (Dry Basis) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Metal | 4.5 | 0.6 | 4.3 | 0.05 | 90.5 | 0.01 | 77.3 | 20.1 | 2.0 | | 0.02 | 0.6 | 0.03 | – | – | 0.5 | 740 |
| Paper | 45.4 | 6.1 | 42.1 | 0.3 | 6.0 | 0.12 | – | – | – | – | – | – | – | – | Trace | 11.3 | 7,930 |
| Plastics | 59.8 | 8.3 | 19.0 | 1.0 | 11.6 | 0.3 | – | – | – | – | – | – | 0.01 | 6.0 | – | 5.1 | 11,500 |
| Leather & Rubber | | | | | | | – | – | – | 2.0 | – | – | – | – | – | 6.4 | 10,175 |
| Textiles | 46.2 | 6.4 | 41.8 | 2.2 | 3.2 | 0.2 | – | – | – | – | – | – | 0.03 | – | – | 3.9 | 8,030 |
| Wood | 48.3 | 6.0 | 42.4 | 0.3 | 2.9 | 0.11 | – | – | – | – | – | – | 0.05 | – | – | 14.1 | 8,400 |
| Food Wastes | 41.7 | 5.8 | 27.6 | 2.8 | 21.9 | 0.25 | – | – | – | – | – | – | 0.24 | – | – | 5.3 | 8,540 |
| Yard Wastes | 49.2 | 6.5 | 36.1 | 2.9 | 5.0 | 0.35 | – | – | – | – | – | – | 0.04 | – | – | 19.3 | 7,300 |
| Glass | 0.52 | 0.07 | 0.36 | 0.03 | 99.02 | – | – | – | – | – | – | – | – | – | – | 0.4 | 65 |
| Miscellaneous | 13.0* | 2.0* | 12.0* | 3.0* | 70.0 | – | – | – | – | – | – | – | – | – | – | 7.5 | 3,500 |

* estimated (varies widely)

** excludes phosphorus in $CaPO_4$

The sensitivity of the forecast results to errors in base year refuse composition, however, is not great. Estimates of national levels of air pollution from incineration based on these results will be similarly acceptable. For a given incinerator at a given instant in time, the projections and also the reference base may have limited validity but the following deals with the *national* problem of solid waste load, refuse properties, and incinerator air pollution.

### 1. Development of Indicators for Projection of Per Capita Waste Loads, Refuse Composition, and the Physical and Chemical Nature of Refuse

In order to project the per-capita waste loads and refuse compositions for each state, national indicators were developed for each of the 10 major categories comprising municipal refuse. These indicators reflect the national growth rates (through the year 2000) in the production of the commodities comprising the major (but not necessarily all) sources of each refuse component. These indicator projections for each of the 10 major refuse components will be found in Appendix G. The indicator for plastics, as an example, was developed from weighted averages of the consumption projections for plastics used in packaging, housewares, furniture, toys, and synthetic-nonwoven textiles. These are major sources of plastics in municipal wastes. Projections of the consumption of these segments of the plastics market should, therefore, provide a realistic tool for estimating the growth of plastics in municipal refuse.

It should be noted that there are varying "lag times" between the purchase and disposal of the various components of refuse. These lag times have been estimated and incorporated into the development of these national indicators for categories which are changing rapidly. Plastics packaging, for example, has substantially no lag time associated with its disposal. Plastics in furniture, however, may have lag times varying from a few years to 30 years or longer, depending on the type of furniture and its use. An average lag time of 10 years was estimated for plastics in furniture.

These indicators *are not* in themselves national projections of the quantities of the various components contained in the national refuse. Each indicator merely projects the national growth rates of materials and goods comprising that classification of refuse with appropriate adjustments for lag time between consumption and disposal.

The projected national annual growth rates ($g'_i$ in the equations developed below) of each of the 10 major refuse components as obtained from the indicator projections are shown in Table IV-11. These annual growth rates were incorporated into equations (see below) to predict the per-capita waste load and refuse composition for any given state in the United States through the year 2000. For some components, such as food wastes, rubber and leather, and wood, the annual growth rate is predicted to remain relatively constant, pacing the increase in population. The annual growth rate of plastics, metal, and glass are predicted to

## TABLE IV–11

## AVERAGE ANNUAL REFUSE CATEGORY INDICATOR GROWTH RATES ($g_i'$)

| Time Period From | To | Paper Products | Miscellaneous & Food Wastes | Metal | Glass | Plastics | Textiles | Rubber & Leather | Wood | Yard Wastes |
|---|---|---|---|---|---|---|---|---|---|---|
| 1968 | 1970 | 4.5% | 1.1% | 4.0% | 5.4% | 11.9% | 4.1% | 3.2% | 1.0% | 2.6% |
| 1970 | 1975 | 4.5% | 1.1% | 4.0% | 5.4% | 11.9% | 4.1% | 3.2% | 1.0% | 2.6% |
| 1975 | 1980 | 3.6% | 1.1% | 3.9% | 3.9% | 11.4% | 3.6% | 3.2% | 0.9% | 2.6% |
| 1980 | 1985 | 3.7% | 1.8% | 2.8% | 2.6% | 5.6% | 4.6% | 3.3% | 1.1% | 2.6% |
| 1985 | 1990 | 4.2% | 1.6% | 2.7% | 2.1% | 5.6% | 4.7% | 3.3% | 1.0% | 2.6% |
| 1990 | 1995 | 3.9% | 1.5% | 1.5% | 1.7% | 5.0% | 4.4% | 3.7% | 0.8% | 2.6% |
| 1995 | 2000 | 4.0% | 1.4% | 0.4% | 0.8% | 4.7% | 3.9% | 3.7% | 0.9% | 2.6% |

vary considerably. Plastics, for example, are predicted to have significant growth rates through 1980, but then to level off at a relatively stable growth rate of about 5% per year.

## 2. Development of Equations for Projecting Per-Capita Refuse Rate and Composition of Refuse for Any State or Region in the United States

The equations shown in Table IV-12 were developed to allow use of the commodity consumption projections prepared by trade associations, the U.S. Department of Commerce, and similar agencies. For illustrative purposes, the equations are written to allow projection of refuse quantity and composition over the time span from the base year (1968) to year "j" (say 1970). Projections from 1970 to 1975 would use the same functional relationships by substituting 1970 for 1968 and 1975 for j. A similar shift is used in subsequent five-year steps to the year 2000.

Equations (5) and (9) permit estimation of the total annual collected waste for disposal and the corresponding refuse composition for any state in the United States through the year 2000, providing data are available for the percent collected, $F_j$, per-capita refuse load, $\Gamma_\beta$, and the base year refuse composition, $X_{i\beta}$.

It should be noted that both the national annual indicator and population growth rates, $g'_i$ and $g'_{pop}$ are not constant but may vary from year to year, as seen in Table IV-11. In the computer program used to implement the projection model, these variations in annual growth rate were taken into account. Schedule C population growth rates were used as it was felt that these estimates were in better agreement with the bases used for the growth rates of the various commodities comprising the refuse category growth indicators.

A basic assumption implicit in utilizing these equations and national indicators to project the local quantity and nature of collected municipal refuse is that the growth rate, for a given refuse category in each specific state or region within the United States, is assumed equal to the national growth rate for that category. This assumption is generally true, but there may be several exceptions. For example, the quantities of glass disposed of nationally might increase 10% over a 10-year period. Due to passage of local regulations prohibiting use of "one-way" beverage bottles, however, the growth rate of discarded glass might be quite different in various states or regions throughout the country.

## TABLE IV-12

## EQUATIONS FOR PROJECTING THE QUANTITY AND COMPOSITION OF DOMESTIC AND COMMERCIAL REFUSE

Let:

$L_j$ = The total collected refuse quantity within a specific state or region in the $j^{th}$ year.

$L_{ij}$ = The quantity of the $i^{th}$ refuse component generated within a specific state or region in the $j^{th}$ year.

$\Gamma_j$ = The per-capita total quantity of refuse generated within a specific state or region in the $j^{th}$ year.

$\Gamma_{ij}$ = The per-capita quantity of the $i^{th}$ component of refuse generated within a specific state or region in the $j^{th}$ year.

$P_j$ = The population of a specific state or region in the $j^{th}$ year.

$X_{ij}$ = The weight fraction of the $i^{th}$ component of refuse generated within a specific state or region in the $j^{th}$ year.

$\Gamma'_{ij}$ = The national per-capita refuse quantity of the $i^{th}$ component generated in the $j^{th}$ year.

A. Local Refuse Load ($L_j$)

$$L_j = F_j P_j \Gamma_j \tag{1}$$

$$\cong F_j P_j \sum_{i=1}^{N} \Gamma_{i\beta} \frac{\Gamma'_{ij}}{\Gamma'_{i\beta}} \tag{2}$$

$$= F_j P_j \sum_{i=1}^{N} \Gamma_{\beta} X_{i\beta} \frac{\Gamma'_{ij}}{\Gamma'_{i\beta}} \tag{3}$$

$$= F_j P_j \Gamma_{\beta} \sum_{i=1}^{N} X_{i\beta} \frac{1}{\Gamma'_{i\beta}} \Gamma'_{i\beta} \frac{(1+g'_i)^{(j-1968)}}{(1+g'_{pop})^{(j-1968)}} \tag{4}$$

$$L_j = F_j P_j \Gamma_{\beta} \sum_{i=1}^{10} X_{i\beta} \frac{(1+g'_i)^{(j-1968)}}{(1+g'_{pop})^{(j-1968)}} \tag{5}$$

B. Local Refuse Composition ($X_{ij}$)

$$X_{ij} = \frac{L_{ij}}{L_j} \tag{6}$$

## TABLE IV-12 (Continued)

$g'_{pop}$ = The annual growth rate of the national population*

$$\cong \frac{L_{i\beta}\,(1+g'_i)^{(j-1968)}}{\sum_{i=1}^{N} L_{i\beta}\,(1+g'_i)^{(j-1968)}} \qquad (7)$$

$g'_i$ = The annual growth rate of the national indicator for the $i^{th}$ refuse component.

$$= \frac{L_{\beta} X_{i\beta}\,(1+g'_i)^{(j-1968)}}{L_{\beta}\,\Sigma X_{i\beta}\,(1+g'_i)^{(j-1968)}} \qquad (8)$$

$F_j$ = The fraction of total solid waste generated in the $j^{th}$ year which is collected for disposal.

$$X_{ij} = \frac{X_{i\beta}\,(1+g'_i)^{(j-1968)}}{\sum_{i=1}^{N} X_{i\beta}\,(1+g'_i)^{(j-1968)}} \qquad (9)$$

Where the Greek letter $\beta$ appears in subscripts, the variable subscripted refers to the base year, 1968.

Where the prime appears ('), this signifies a national average value.

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*Schedule C – U.S. Bureau of the Census

The total United States population is projected to increase 54% over the 30-year time period analyzed. Thus, communities growing at this same rate should expect a refuse disposal requirement approximately 2.6 times as great due to the increasing per capita refuse generation rate and a net heat disposal load rise of greater than 300% of the current load.

## D. COLLECTED REFUSE PROJECTIONS FOR THE STATE ECONOMIC AREAS

The analysis and data above provide the basis for projection of the quantity of collected refuse in U.S. urban areas [as characterized by the State Economic Areas (SEA's)], the primary stimulus for new incinerator construction. However, two quantities remained unspecified: the 1968 average urban per capita refuse generation rate and the fraction of generated refuse which is collected by the municipalities.

### 1. Refuse Generation Rate

Data on refuse generation rates are extremely difficult to obtain. Differences in collection practices and other disposal patterns throughout the country bias data based on collected refuse quantities. Two states, however (California and New Jersey), have been surveyed in considerable detail by the Bureau of Solid Waste Management. Their evaluation was made using a "material balance" for these states, estimating the movement of potential refuse components into and out of each state and the internal generation of potential refuse components rather than attempting to develop refuse generation rates from the quantities of refuse collected or otherwise appearing for disposal. The values determined by this process were 6.5 and 6 pounds per person per day (ppd) for California, and New Jersey, respectively. Using the approach described previously, these values reduced to 4.8 and 5.17 ppd on a yard waste-free basis. This yields an average per capita refuse generation rate of 5 ppd on a yard waste-free basis for 1968.

It is recognized that using the value of 5 ppd (excluding yard waste) for the national average, based on data from only two states, is at best speculative. It is unlikely, however, that more comprehensive data will be available in the near future. Somewhat pragmatically, therefore, it was felt that this value could serve as a national reference point. The value of a 6-ppd refuse generation rate for New Jersey was considered the more accurate of the two values available. The New Jersey value was, therefore, selected as the reference state in evaluating the yard waste contribution. Consistent with the analysis described above and noting that New Jersey is a state with 209 frost-free days, the following equation was used to develop, on a state-by-state basis, the average total refuse generation rate for 1968:

$$5 + \left(\frac{\text{No. of Frost-Free Days}}{365}\right)(1.8) = \text{lbs per Capita per Day in a Given State}$$

The equation shown above was used to produce the per capita refuse generation numbers shown in Table IV-15, and by comparison with recent Bureau of Solid Waste Management data on collected refuse quantities, produced estimates for 1968 "percent collected" on a state-by-state-basis for the urban areas. The urban areas are of primary interest as regards incineration, as high population density (low land availability) and high total population (high refuse generation density) provide the incentives and financial resources necessary for incinerator construction.

### 2. National Sea Collected Refuse Quantity

The per capita collected refuse quantity can be calculated in two ways:

- The preceding paragraphs provide the basis to calculate, on a simplistic basis, the average quantity of collected refuse using:
  a. The national average per capita refuse generation rate using 5.6 ppd (the average of the values in Table IV-15 as the base for 1968);

  b. The national average of 69% collected in 1968 (the average of the values in Table IV-15), followed by a linear increase to 95% collected in 2000;

  c. An average set of per capita refuse generation multipliers (say for a semiseasonal state) from Table IV-14.

- A more rigorous analysis can be made to compute the per-capita quantity of collected refuse, weighted by the population and refuse composition on a state-by-state basis using:
  a. The 1968 per-capita refuse generation rate for each state (Table IV-15);

  b. The 1968 percent collected for each state (Table IV-15), allowing for a linear increase to 95% in 2000;

  c. The population and population growth in the urban areas of each state as characterized by the State Economic Areas – SEA's – from Schedule D of the U.S. Census Bureau (and ADL extrapolations after 1985);

d. The per-capita refuse generation multipliers developed on a state-by-state basis (but derived, as presented above, from national commodity growth indicators).

In the first case, the product of 1968 average per-capita refuse generation rate, per-capita multiplier and fraction collected directly yields per-capita collected refuse quantity forecasts. In the second case, the data are used to develop a forecast of total SEA refuse quantity and, combined with forecast national SEA population totals, to yield the weighted per-capita collected refuse quantity.

The results of these two approaches to develop per capita collected refuse quantity are shown in Figure IV-1. It should be noted that the more rigorous analysis produces the higher estimate. Although it is recognized that a number of critical assumptions have been made in the development of this projection model and in projecting refuse collection practices, it is clear that the quantity of collected refuse within U.S. municipalities will increase drastically over the next 30 years.

In Chapter VI, the results of an analysis are presented which forecast the active incinerator capacity through the year 2000. In the course of that analysis, the populations in the State Economic Areas (SEA's) were forecast based upon the U.S. Census Bureau Schedule D projection through 1985 with extrapolation by ADL to the year 2000. The total population in the SEA areas of the U.S. are shown in Table IV-16. This population can be multiplied by the per capita collected refuse quantity burden values shown in the upper curve in Figure IV-1 to produce the total SEA (urban) refuse disposal requirement shown in Figure IV-2. The results of such a computation show an almost four-fold growth in the refuse disposal requirement in our urban centers over the next 30 years, reflecting the compounding effect of per capita collected refuse quantity with population growth.

The results of this analysis show the growing proportions of the solid waste disposal crisis even now facing many of our cities. Although, from a cost standpoint, conventional incineration may not appear to be the optimum path, it is clear that additional incinerator capacity, in balance with other new and powerful waste disposal and waste recovery concepts, will be required to meet this challenge. The anticipated growth in incineration capacity suggests the need to explore the air pollution potential, its nature and causes, associated with incinerators. This subject is discussed in Chapter V.

### 3. Refuse Generation Projections for Three U.S. Regions

The refuse compositions of the three general climate regions shown in Table IV-8 serve as a basis from which to forecast the physical and chemical nature of refuse in each region through the year 2000. The projected refuse composition values are shown in Table IV-13. Other computed refuse properties and statistics are illustrated in Table IV-14. These calculated values represent our best estimate of the average annual refuse properties in future years. As such, they are useful in showing trends in various parameters affecting incinerator performance and solid waste load.

The results of our analysis show several significant changes in the nature of refuse over the next 30 years. The effects vary in magnitude, but few will be helpful to the incinerator operator.

#### a. Refuse Composition

*(1) Glass* – The projections show that the fraction of glass in refuse will not change significantly over the next 30 years. This projection could change greatly (downward), however, if low cost beverage and food grade plastic containers are developed. The impact would be still greater if degradable plastic containers are developed.

*(2) Metal* – The projections show a slight drop in the metal content of refuse, although on a total weight-discarded basis (considering the growth in per-capita rate and population), the amounts may increase slightly in a given community. The economics of metal recovery operations, therefore, should not be expected to vary as a result of changes in the amount of metal present.

*(3) Paper* – Continuing its historical upward trend, paper, cardboard, and other wood-fiber products will comprise the dominant fraction of refuse. This growth (30-35% by 2000) will decrease refuse bulk density, adversely affecting almost all refuse collection, storage and handling operations associated with refuse disposal facilities. The increase may have a favorable impact on the economics of waste paper recovery. This practice should become of increasing importance in light of the diminishing availability of new pulp resources forecast for the late 1980's.

*(4) Plastics* – The almost 400% growth in the plastics fraction of refuse indicates that operating problems associated with the burning of this waste component can be expected to increase.

## TABLE IV-13

## PROJECTED REFUSE COMPOSITIONS (%)*

| Refuse Category | 1968 Seasonal | 1968 Semi-Seasonal | 1968 Non Seasonal | 1970 Seasonal | 1970 Semi-Seasonal | 1970 Non Seasonal | 1975 Seasonal | 1975 Semi-Seasonal | 1975 Non Seasonal | 1980 Seasonal | 1980 Semi-Seasonal | 1980 Non Seasonal | 1990 Seasonal | 1990 Semi-Seasonal | 1990 Non Seasonal | 2000 Seasonal | 2000 Semi-Seasonal | 2000 Non Seasonal |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Glass | 8.8 | 8.1 | 7.6 | 9.1 | 8.4 | 7.9 | 9.9 | 9.2 | 8.7 | 10.3 | 9.6 | 9.0 | 9.5 | 8.9 | 8.4 | 8.1 | 7.6 | 7.2 |
| Metal | 8.7 | 8.1 | 7.5 | 8.8 | 8.2 | 7.6 | 9.0 | 8.4 | 7.8 | 9.3 | 8.7 | 8.1 | 9.0 | 8.4 | 7.9 | 7.4 | 6.9 | 6.5 |
| Paper | 38.2 | 35.1 | 32.6 | 39.1 | 35.8 | 33.5 | 40.8 | 37.6 | 35.2 | 41.5 | 38.4 | 36.1 | 45.0 | 41.7 | 39.3 | 49.7 | 46.0 | 43.5 |
| Plastics | 1.1 | 1.1 | 1.0 | 1.3 | 1.3 | 1.1 | 1.9 | 1.8 | 1.7 | 2.8 | 2.7 | 2.5 | 3.5 | 3.5 | 3.1 | 4.2 | 4.2 | 3.8 |
| Leather and Rubber | 1.5 | 1.4 | 1.3 | 1.5 | 1.4 | 1.3 | 1.5 | 1.4 | 1.3 | 1.5 | 1.4 | 1.3 | 1.5 | 1.4 | 1.3 | 1.6 | 1.5 | 1.4 |
| Textiles | 2.0 | 1.9 | 1.8 | 2.0 | 1.9 | 1.8 | 2.1 | 2.0 | 1.9 | 2.1 | 2.0 | 1.9 | 2.5 | 2.3 | 2.2 | 2.8 | 2.6 | 2.5 |
| Wood | 2.7 | 2.4 | 2.3 | 2.5 | 2.3 | 2.2 | 2.2 | 2.0 | 1.9 | 2.0 | 1.8 | 1.7 | 1.6 | 1.5 | 1.4 | 1.3 | 1.2 | 1.2 |
| Food Wastes | 21.1 | 19.5 | 18.2 | 20.2 | 18.7 | 17.4 | 17.9 | 16.6 | 15.5 | 16.2 | 15.0 | 14.1 | 14.0 | 13.1 | 12.3 | 12.1 | 11.4 | 10.7 |
| Miscellaneous | 1.8 | 1.7 | 1.6 | 1.7 | 1.6 | 1.5 | 1.5 | 1.4 | 1.3 | 1.4 | 1.3 | 1.2 | 1.2 | 1.1 | 1.1 | 1.0 | 1.0 | 0.9 |
| Yard Wastes | 14.1 | 20.7 | 26.1 | 13.8 | 20.4 | 25.7 | 13.2 | 19.6 | 24.7 | 12.9 | 19.1 | 24.1 | 12.2 | 18.1 | 23.0 | 11.8 | 17.6 | 22.3 |
| Total | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |

*Percentages shown are by weight on an "as discarded" basis

## TABLE IV-14

## PROJECTED GENERATED REFUSE PROPERTIES AND STATISTICS FOR THREE CLIMATE REGIONS

| Refuse Properties and Statistics | 1968 | | | 1970 | | | 1975 | | | 1980 | | | 1990 | | | 2000 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Seasonal | Semi-Seasonal | Non Seasonal | Seasonal | Semi-Seasonal | Non Seasonal | Seasonal | Semi Seasonal | Non Seasonal | Seasonal | Semi-Seasonal | Non Seasonal | Seasonal | Semi-Seasonal | Non Seasonal | Seasonal | Semi-Seasonal | Non Seasonal |
| Heating Value (HHV, Btu/lb) | 4582 | 4505 | 4449 | 4628 | 4550 | 4493 | 4719 | 4640 | 4582 | 4811 | 4730 | 4627 | 5040 | 4956 | 4849 | 5407 | 5271 | 5161 |
| Percent Moisture | 25.9 | 27.8 | 29.3 | 25.2 | 27.1 | 28.6 | 23.4 | 25.3 | 26.9 | 22.1 | 24.0 | 25.7 | 20.5 | 22.4 | 24.1 | 19.3 | 21.3 | 22.9 |
| Percent Volatile Carbon | 19.8 | 19.4 | 19.1 | 19.9 | 19.5 | 19.2 | 20.4 | 20.0 | 19.7 | 20.8 | 20.4 | 20.1 | 22.0 | 21.5 | 21.1 | 23.6 | 23.0 | 22.5 |
| Percent Ash Content | 21.8 | 20.3 | 19.1 | 22.1 | 20.7 | 19.5 | 22.9 | 21.5 | 20.3 | 23.5 | 22.0 | 20.3 | 22.4 | 21.1 | 20.0 | 19.7 | 18.6 | 17.7 |
| Percent Ash (excluding glass, metals) | 5.5 | 5.3 | 5.1 | 5.5 | 5.2 | 5.1 | 5.3 | 5.1 | 4.9 | 5.2 | 5.0 | 4.9 | 5.2 | 5.0 | 4.9 | 5.3 | 5.2 | 5.0 |
| Per Capita Refuse Quantity Multiplier | 1.0 | 1.0 | 1.0 | 1.05 | 1.05 | 1.05 | 1.19 | 1.18 | 1.18 | 1.32 | 1.32 | 1.31 | 1.52 | 1.51 | 1.50 | 1.76 | 1.74 | 1.72 |
| National Population Growth Multiplier | 1.0 | 1.0 | 1.0 | 1.02 | 1.02 | 1.02 | 1.07 | 1.07 | 1.07 | 1.13 | 1.13 | 1.13 | 1.33 | 1.33 | 1.33 | 1.54 | 1.54 | 1.54 |
| Total Generated Refuse Quantity Multiplier | 1.0 | 1.0 | 1.0 | 1.07 | 1.07 | 1.07 | 1.27 | 1.26 | 1.26 | 1.49 | 1.49 | 1.48 | 2.02 | 2.01 | 2.00 | 2.71 | 2.68 | 2.65 |
| Per Capita Heat Rate Multiplier (Btu/person/day) | 1.0 | 1.0 | 1.0 | 1.06 | 1.06 | 1.06 | 1.23 | 1.22 | 1.22 | 1.39 | 1.39 | 1.36 | 1.67 | 1.66 | 1.64 | 2.08 | 2.04 | 2.00 |
| Total Heat Rate Multiplier (Btu/day) | 1.0 | 1.0 | 1.0 | 1.08 | 1.08 | 1.08 | 1.32 | 1.31 | 1.31 | 1.57 | 1.57 | 1.54 | 2.22 | 2.21 | 2.18 | 3.20 | 3.14 | 3.08 |

## TABLE IV-15

## U.S. REFUSE GENERATION AND COLLECTION

| | 1968 Per Capita Refuse Rate (pounds/day) | | | |
|---|---|---|---|---|
| | Generated*** | Collected | | |
| State | Urban | Urban | Urban Percent* | Rural |
| Alabama | 6.42 | 2.32 | 36 | 2.64 |
| Arizona | 6.51 | ** | 95 | – |
| Arkansas | 6.20 | 2.94 | 47 | 4.06 |
| California | 6.80 | 7.58 | 95 | 7.62 |
| Colorado | 5.81 | 7.41 | 95 | 8.09 |
| Connecticut | 5.89 | 6.45 | 95 | 7.30 |
| Delaware | 5.94 | 7.85** | 95 | 0.85 |
| Florida | 6.80 | 3.91 | 58 | 3.41 |
| Georgia | 6.20 | 2.90 | 47 | 2.61 |
| Idaho | 5.84 | 3.53 | 60 | 0.31 |
| Illinois | 5.95 | – | 69 | – |
| Indiana | 5.95 | 3.44 | 58 | 2.56 |
| Iowa | 5.90 | 6.35** | 95 | 0.98 |
| Kansas | 6.03 | 4.17 | 69 | 1.57 |
| Kentucky | 6.08 | 3.84 | 63 | 1.22 |
| Louisiana | 6.44 | 4.34 | 67 | 2.36 |
| Maine | 5.83 | – | 69 | – |
| Maryland and D.C. | 6.15 | 4.47 | 73 | 3.08 |
| Massachusetts | 5.94 | – | 69 | – |
| Michigan | 5.89 | 2.66 | 45 | 3.64 |
| Minnesota | 5.82 | 2.78 | 48 | – |
| Mississippi | 6.22 | 3.03 | 49 | 2.98 |
| Missouri | 6.08 | 4.68 | 77 | 2.20 |
| Montana | 5.67 | 9.08** | 95 | 1.62 |
| Nebraska | 5.92 | – | 69 | – |
| Nevada | 5.70 | 5.58 | 95 | – |
| New Hampshire | 5.70 | – | 69 | – |
| New Jersey | 6.03 | 6.02 | 95 | 3.37 |
| New Mexico | 5.97 | 2.47 | 41 | 0.61 |
| New York | 6.08 | 3.32 | 55 | 4.40 |
| North Carolina | 6.18 | 5.30 | 86 | – |
| North Dakota | 5.67 | 4.42 | 78 | 5.29 |
| Ohio | 5.96 | 3.61 | 61 | 3.65 |
| Oklahoma | 6.10 | 3.96 | 65 | 1.87 |
| Oregon | 6.34 | 3.05 | 48 | – |
| Pennsylvania | 6.14 | 4.28 | 70 | 4.26 |
| Rhode Island | 5.97 | 1.66 | 69 | 3.10 |
| South Carolina | 6.24 | 5.90 | 95 | 2.79 |
| South Dakota | 5.74 | – | 69 | – |
| Tennessee | 6.17 | 2.62 | 42 | 1.42 |

### TABLE IV-15 (Continued)

| | 1968 Per Capita Refuse Rate (pounds/day) | | | |
|---|---|---|---|---|
| | Generated*** | Collected | | |
| State | Urban | Urban | Urban Percent* | Rural |
| Texas | 6.23 | 3.57 | 57 | 1.78 |
| Utah | 5.99 | 5.97 | 95 | 1.74 |
| Vermont | 5.73 | – | 69 | – |
| Virginia | 6.25 | 4.36 | 70 | 1.85 |
| Washington | 6.36 | 3.53 | 55 | 0.22 |
| West Virginia | 5.95 | 2.17 | 36 | 0.52 |
| Wisconsin | 5.92 | – | 69 | – |
| Wyoming | 5.64 | – | 69 | – |
| Alaska | 5.86 | – | 69 | – |
| Hawaii | 6.80 | 1.65* | 69 | 1.30 |

*Set equal to 95% if reported "collected" is greater than calculated "generated" and to 69% (average for states where value can be calculated) if "collected" is unknown.

**Data incomplete or not credible.

***Calculated, see Section IVD for derivation.

**Sources:** Reference 2 and ADL estimates.

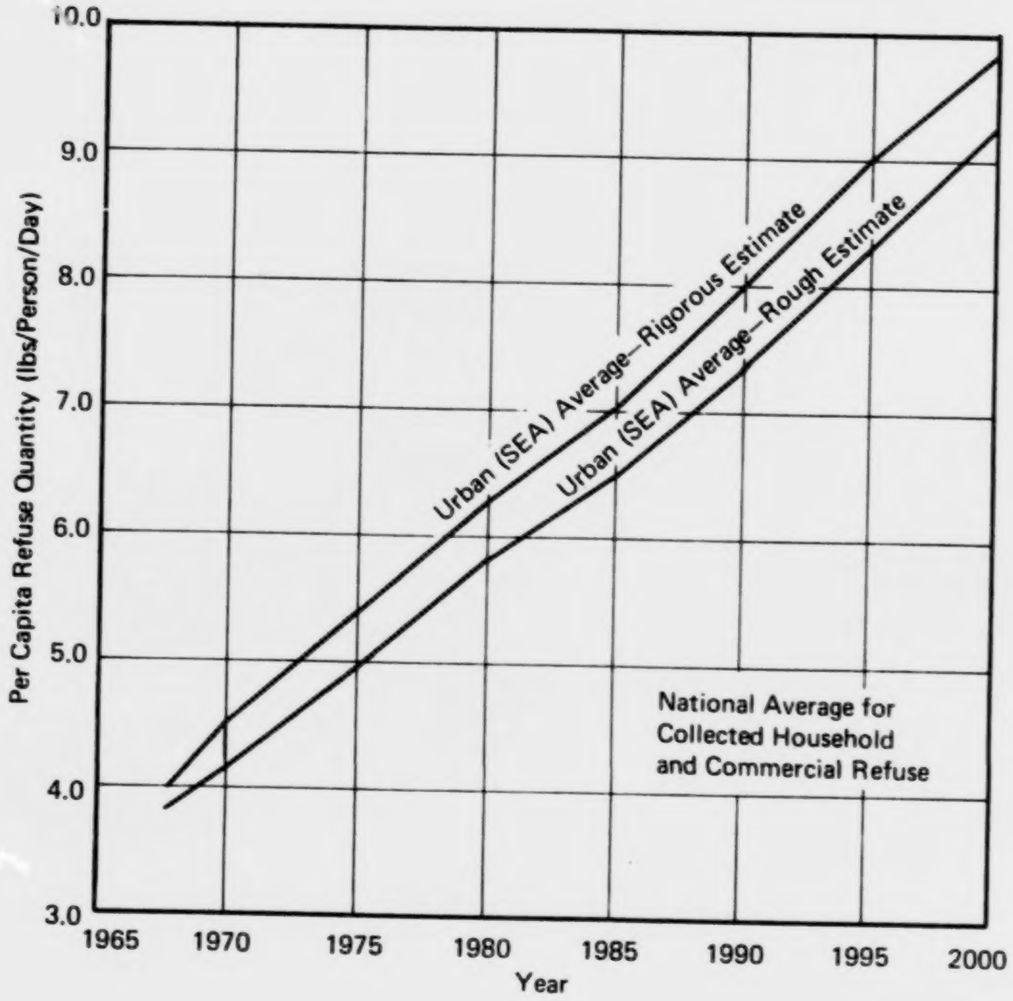

FIGURE IV–1 PROJECTED PER CAPITA REFUSE QUANTITY

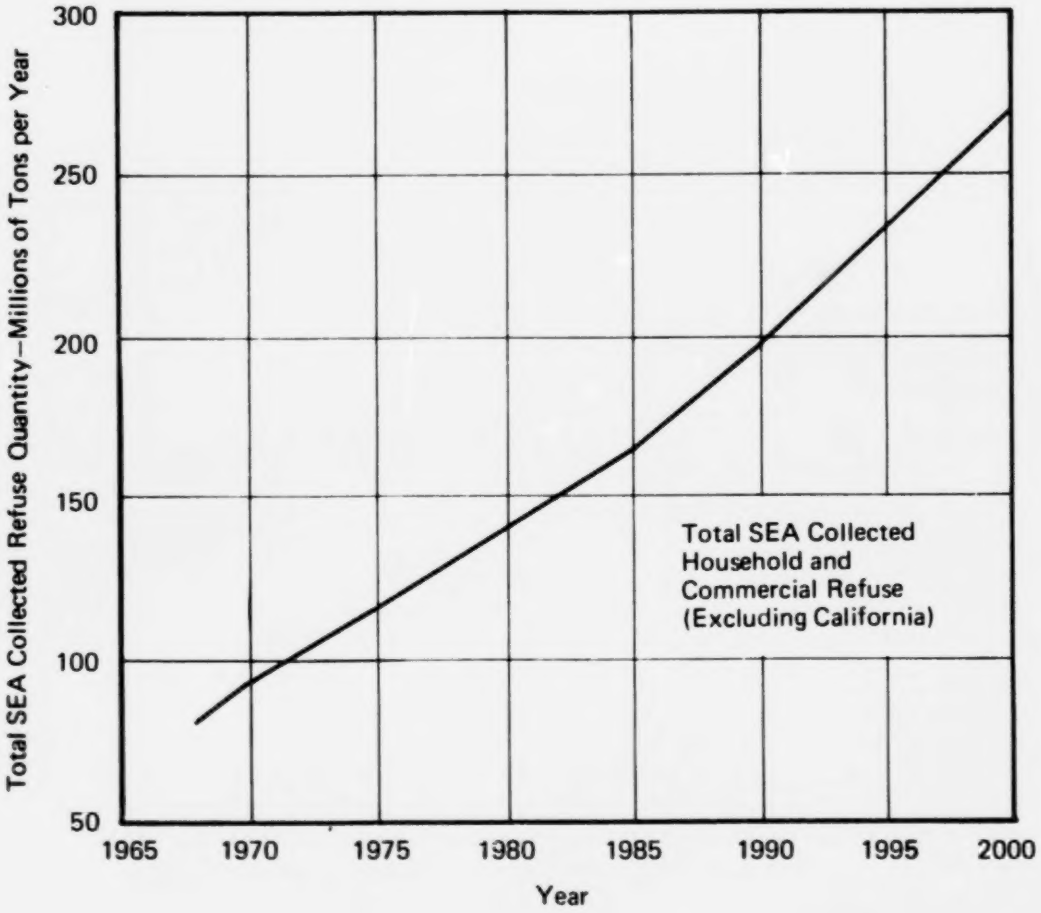

FIGURE III–1 PROJECTED COLLECTED REFUSE QUANTITY

### b. Refuse Incineration Characteristics

*(1) Heating Value* – Refuse heating value (Btu/lb) can be expected to increase at a slow but regular rate throughout the 30-year period. Since an incinerator is, in effect, a heat disposal system, the increase in heating value can be expected to yield a roughly corresponding decrease in the capacity of furnaces. Thus, a unit designed for a peak of 250 tons per day of 1968 refuse may have a usable capacity of only 215 tons per day by 2000.

*(2) Moisture* – The indicated drop in average refuse moisture would result in increased flue gas temperatures with corresponding decrease in effective incinerator capacity. This parameter is greatly influenced by refuse storage practices and local weather conditions. Thus, excursions from the predicted values are expected. The indicated trend toward diminishing weight fractions of yard and food waste in refuse, however, will tend to reduce average content below past local average values.

*(3) Volatile Carbon* – The volatile carbon content of refuse (calculated as total minus fixed carbon) affects the fraction of combustion taking place in the furnace volume and the rate of formation of soot as opposed to the combustion on the grates. The slow but steady increase in this parameter (19% over the 30 years) will place an increasing emphasis on the realization of satisfactory overfire air mixing and flue gas residence time prior to quenching. Inadequate design or operation with respect to these quantities may yield increases in the combustible particulate, carbon monoxide and hydrocarbon content of the effluent flue gas.

*(4) Ash Content* – Our projections show an increase, then a decrease, in total refuse ash content. This parameter is of importance as it affects residue disposal. The effects here will be small. In addition, the ash content of refuse, excluding glass and metals, can be expected to remain relatively constant. This suggests that the mineral particulate furnace emission factors, shown in Chapter V to be directly related to this parameter, will also remain relatively constant.

### c. Refuse Generation Rate

During the next 30 years, a continued increase of the per capita refuse generation rate to a value of more than 70% above the current level is expected. Compounded by the effect of increasing refuse heat content, the equivalent per capita heat disposal demand will rise to about twice the current level. Thus, communities with a stable population level would experience a refuse disposal requirement increase of 70% and an incineration "capacity" increase of 100% relative to 1968.

### TABLE IV-16

### U.S. POPULATION IN STATE ECONOMIC AREAS***

| Year | Population |
|---|---|
| 1968 | 108,872,590* |
| 1970 | 110,966,370* |
| 1975 | 116,488,450* |
| 1980 | 112,402,290* |
| 1985 | 128,742,620* |
| 1990 | 135,547,810** |
| 1995 | 142,860,400** |
| 2000 | 150,727,520** |

***Source:** Schedule D, U.S. Census Bureau

****Source:** Arthur D. Little, Inc., estimates

***Excludes California – Note also that there are no SEA's in Vermont, the Dakotas, Wyoming, Montana, Idaho and Alaska.

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# V. THE NATURE AND CAUSES OF INCINERATOR AIR POLLUTION

# V. THE NATURE AND CAUSES OF INCINERATOR AIR POLLUTION

## A. INTRODUCTION

The preceding Chapter suggests the growing proportions of the solid waste disposal problems facing municipal governments. The rapidly increasing quantity of waste forecast by that analysis is only one of the many incentives which will spur the construction of new incinerator plants in the future. Knowledge of the nature and causes of air pollution from incinerators is badly needed to assist in the selection, design and operation of both new and existing plants. With such understanding, the air pollution problem posed by these plants can be reduced or eliminated. Incineration and air pollution need not, indeed must not, be synonymous.

The pollutants associated with incinerators fall into three classes: particulate (both mineral and combustible), combustible gases (carbon monoxide, hydrocarbons, and polynuclear hydrocarbons), and noncombustible gases (nitrogen oxides, sulfur oxides, and hydrogen chloride). The mechanisms by which these pollutants arise in the course of incineration are discussed, mainly in this section of the report. However, the reader unfamiliar with incinerator systems and the pertinent principles of combustion should review Sections B and C of Appendix H as this background is assumed in the analysis and discussions which follow.

Air pollutants may be generated or consumed in many places and under many conditions in the incineration systems. It is important, therefore, to define several terms to avoid ambiguity.

- *Emission Rate.* This term refers to the weight flow of constituents of an incinerator flue gas stream which are of concern regarding air pollution.

- *Furnace Emissions.* This term refers to the emission rate *prior* to substantive air pollution abatement treatment. Thus, with the exception of any settling of particulate in the breeching, furnace emissions reflect the maximum air pollution potential of an incinerator.

- *Stack Emissions.* This term refers to the emission rate following the air pollution control device. As such, stack emissions represent the actual air pollution potential of an incinerator.

- *Emission Factor.* This term refers to the emission rate (either stack or furnace type) normalized to some standard; in this discussion, usually a ton of as-fired refuse. Emission factors are ideally related to aspects of system design, operating practices, and refuse composition to permit a definitive statement as to the total emissions characterizing a given plant disposing of a specified amount of refuse.

In order to characterize the emissions and develop the emission factors characteristic of municipal incinerators, recourse must be made to existing data. Using theory, these data can be analyzed to extract general truths about the system's behavior. This approach is necessary because of the complexity of the incineration process and the lack of detailed engineering data to test purely theoretical models. The data bank upon which much of this discussion depends can be found in Appendix J. Some additional data are included in tables throughout the discussion which follows.

## B. PARTICULATE EMISSIONS

### 1. Emission Units

Particulate emissions are reported in a wide range of units the most common of which are:

- lb/ton of refuse
- lb/1000 lb flue gas corrected to 50% excess air
- lb/1000 lb flue gas corrected to 12% $CO_2$
- grains/standard cubic foot (60°F, 1 atm) at 50% excess air
- grains/standard cubic foot (60°F, 1 atm) at 12% excess air
- grains/standard cubic foot (60°F, 1 atm) at stack conditions
- grams/cubic meter at NTP (32°F, 1 atm) and 7% $CO_2$

In order to compare data from different sources it has been necessary to develop conversion factors between the different sets of units. Unfortunately the conversion factors depend on the fuel composition and the operating conditions in a particular incinerator, factors which are often not reported; consequently, the conversion factors reported in Table V-1 have been derived for a representative set of conditions and are based on the refuse stoichiometry in Appendix C. Errors resulting from variations in the conversion factors between different units will be small compared to those introduced by other uncertainties in emission data. More detailed discussions of the factors that determine the conversion factors are presented by Kaiser[1], Rehm[2, 3] and Marshalla et al.[4]

In the following sections the emission factors will be reported in units of lb/ton of refuse (as fired) since this unit relates to the quantity most frequently measured at municipal incinerators. An additional reason for preferring this unit to those based on flue gas volume or mass is that these last two can give misleading results when auxiliary burners are used since the mass or volume of the combustion products of the auxiliary burners are added to those originating in the refuse.

It should be noted that when a supplementary fuel is used or if the refuse differs significantly from that of our reference composition, the conversion factors in Table V-1 may be in error by factors of two or more. As an illustration of the effect of auxiliary burners on conversion factors based on stack gas mass or volume, reference is made to Engdahl's tabulation[5] of emission factors for gas-fired domestic incinerators where 1 grain/SCF at 50% excess air corresponds to as much as 100 lb/ton refuse burned.

As an illustration of the effect of refuse composition on conversion factors, the value for different refuse types (Marshalla et al) is given in Table V-2.

Conversion factors for emissions from European units burning refuse having heating values much lower than that of typical American refuse were obtained by interpolation from Table V-2.

### 2. Emission Factors

The mass furnace emission rate for particulates is a function of many variables:

- Undergrate air velocity.
- Refuse ash content.
- Burning rate.
- Furnace temperature.

## TABLE V-1

## CONVERSION FACTORS FOR PARTICULATE INCINERATOR EMISSIONS*

| | Lbs/Ton Refuse (As Received) | Lbs/1000Lbs Flue Gas At 50% Excess Air | Lbs/1000Lbs Flue Gas At 12% $CO_2$ | Grains/SCF At 50% Excess Air | Grains/SCF At 12% $CO_2$ | Grams/$Nm^3$ At NTP, 7% $CO_2$ |
|---|---|---|---|---|---|---|
| Lbs/Ton Refuse (As Received) | 1 | 0.089 | 0.10 | 0.047 | 0.053 | 0.067 |
| Lbs/1000Lbs Flue Gas At 50% Excess Air | 11.27 | 1 | 1.12 | 0.52 | 0.585 | 0.74 |
| Lbs/1000Lbs Flue Gas At 12% $CO_2$ | 10.0 | 0.89 | 1 | 0.46 | 0.52 | 0.66 |
| Grains/SCF At 50% Excess Air | 21.31 | 1.93 | 2.16 | 1 | 1.12 | 1.42 |
| Grains/SCF At 12% $CO_2$ | 18.85 | 1.71 | 1.92 | 0.89 | 1 | 1.26 |
| Grams/$Nm^3$ At NTP, 7% $CO_2$ | 15.0 | 1.36 | 1.53 | 0.704 | 0.79 | 1 |

* Based on refuse of 4,450 Btu/lb higher heating value (Appendix C)

## TABLE V-2

### EFFECT OF REFUSE TYPE ON FACTOR CONVERTING LBS/1000 LBS OF FLUE GAS (at 50% excess air) to lbs/ton

| General Composition | Waste Type | Moisture | Heating Value Btu/lb | Conversion Factor |
|---|---|---|---|---|
| Dry Rubbish | 0 | 10% | 8,500 | 21.4 |
| 80% Rubbish, 20% Garbage | 1 | 25% | 6,500 | 16.7 |
| 50% Rubbish, 50% Garbage | 2 | 50% | 4,300 | 11.7 |
| 35% Rubbish, 65% Garbage | 3 | 70% | 2,500 | 7.75 |

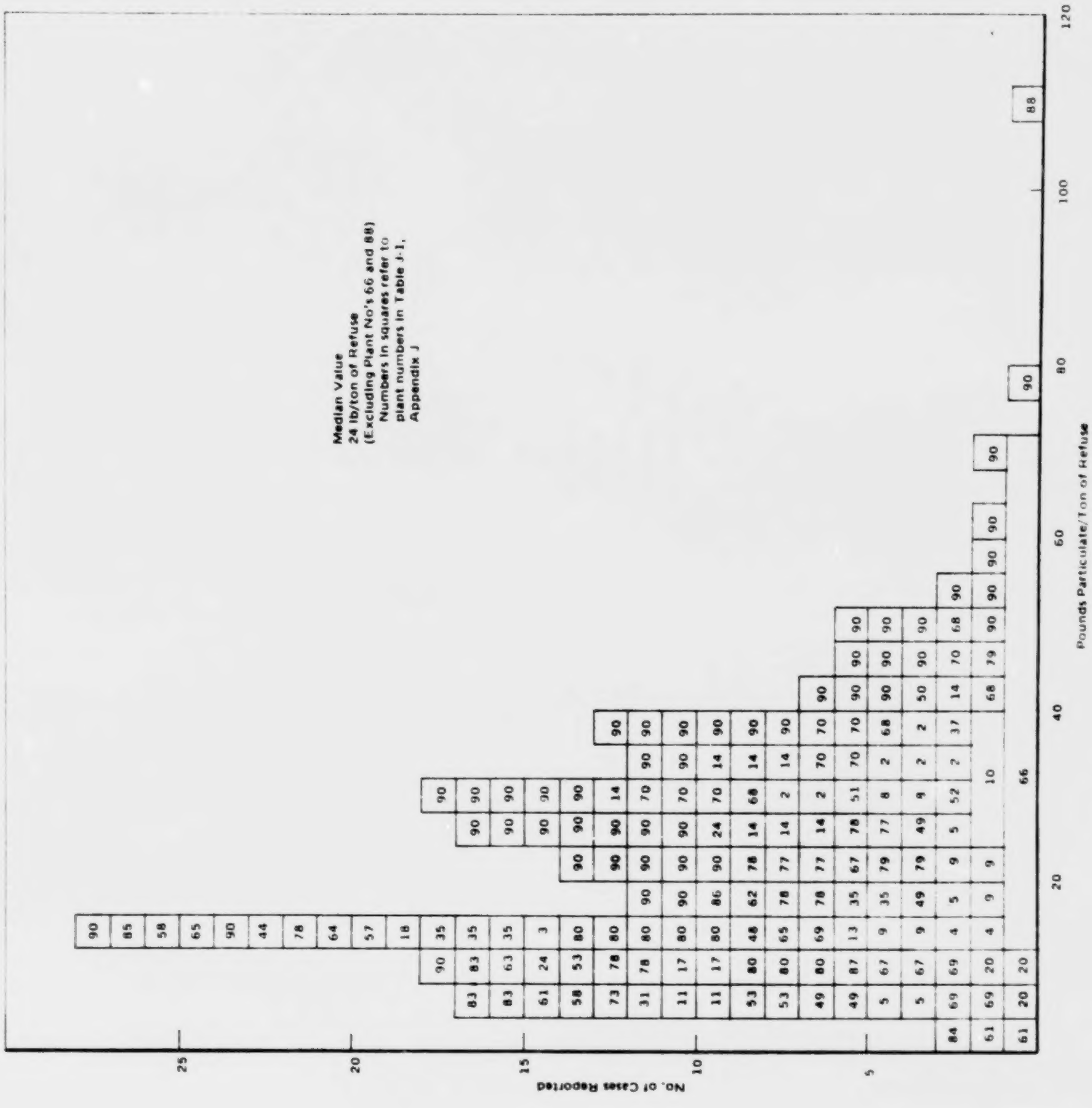
**Source:** Reference 6

- Grate agitation in a continuous feed incinerator; or batch size, method, and frequency of feeding for batch units.
- Combustion chamber design.

Data reported for different units are often insufficiently well-documented to permit the confident separation of the effects of the above variables on the emission rates. The emission data will, therefore, be presented first as a single compilation of all available data; then, for the data that are sufficiently well-documented, in a form that will demonstrate the effect on emission of a limited number of design and operating variables.

a. Units with Capacities in Excess of 50 Tons per 24-Hour Day (TPD)

Figure V–1 presents the furnace particulate rates as a histogram with each block containing the plant number assigned to the furnace (Table J–1 in Appendix J) from which the data were taken. The values reported correspond to emission in the absence of any air pollution control devices, but include data taken at sampling positions varying from the furnace exit to the base of the stack. The data bank includes 183 points obtained on 50 different incinerators. The most common sampling positions are at the inlet of the air pollution control devices or, in the absence of any collectors, at the stack. The values at the outlet



Median Value
24 lb/ton of Refuse
(Excluding Plant No's 66 and 88)
Numbers in squares refer to
plant numbers in Table J-1,
Appendix J

FIGURE V–1 HISTOGRAM OF PARTICULATE FURNACE EMISSION RATES FOR MUNICIPAL INCINERATORS
(Capacity>50 Ton/Day)

of the combustion chamber will therefore usually be higher by amounts that will depend on the particle size distribution, the gas velocities, and the configuration of the ductwork.

Because of the variation in flue gas velocity and particulate loading at the furnace outlet and the difficulty of carrying out a two-dimensional probing of the concentration and velocity profiles, direct measurement of furnace emissions is difficult. One of the most reliable methods of determining the loading at the furnace outlet is the measurement of the fly ash both emitted from the stack and deposited in the ductwork and collection equipment. Data obtained by this method do not show a significant difference from those obtained by sampling at the furnace exit, suggesting that the data of Figure V–1 are not greatly influenced by the variations in sampling location; and we may, therefore, consider such values as furnace emission rates.

The variations in the furnace emission rates compiled in Figure V–1 are far greater than the uncertainty in the individual datum points and are clearly due to the variations in refuse composition, furnace construction, and mode of operation. The spread in the results for a particular furnace (e.g., the seven-fold variation for data on Plant Number 90) is a measure of the effect on emission rate of variations in refuse composition and operating conditions. The differences in the mean emission rate for different units (e.g., the means for Plant Numbers 61 and 90) is a measure of the effect on the emission rate of variations in furnace design. These effects will be considered in greater detail in the following sections.

In the evaluation of a mean emission factor it should be recognized that Figure V–1 was prepared from all accessible furnace emission data and therefore does not present a statistical sample. Biases are introduced in the compilation by:

- The greater number of values shown for those units on which a large number of tests had been performed;
- The greater availability of test data on modern units or units that had been recently modified;
- The probability that operating conditions during test periods are often under closer control than normal; and
- The inclusion of several data points corresponding to stack measurements of furnaces with no APC devices. (The furnace emission factors in these cases are expected to be 15 to 30% higher than the stack values.)

This last factor, which would tend to lower the furnace emission rate, is partially compensated for by the relatively large number of data points for units with reciprocating grates which tend to have higher emissions than the average.

The mean emission factor for the data in Figure V–1, excluding German plants which have unusually high emission factors for reasons to be presented later, is 24 lb/ton. This value may be compared with mean values for furnace emission of 17 lb/ton reported by the PHS[7], 35 lb/ton reported by Fernandes[8], or mean values for stack emissions for furnaces without special fly ash collection devices of 20 lb/ton reported by Rehm[9] and also by Chass and Rose.[10] The mean value does not differ greatly from the statement by Walker[11] that a reasonable dust loading at the entrance of the collector is 2 lb/1000 lb flue gas corrected to 50% excess air, which is equivalent to 22.5 lb/ton.

The mean emission from Figure V–1 including the small number of very high emission German data is 25.5 lb/ton. The median emission, however, is found to be relatively insensitive to whether the German data are included or not.

b. Units with Capacities Under 10 TPD

Emission data on small incinerators are presented as a histogram in Figure V–2. The data bank consists mainly of the California data on single- and multi-chamber batch incinerators[12,13] and the very extensive data on an experimental incinerator obtained by the Public Health Service.[14,15,16] The numbers within the squares refer to the references from which the data were taken. Only the noncombustible portions of the particulate were presented for the data from Reference 16 as the series of tests described in this reference were carried out on a fuel with a high volatile content. The inclusion of the combustible fraction of the emission for these runs would have resulted in emission rates considerably higher than those for the other runs.

The PHS tests systematically varied operating conditions and refuse composition. The spread in the data for these cases gives a direct measure of the relative importance of different variables on the emission values. The mean emission from the small incinerator based on 121 data points is 3.25 lb/ton; not very different from the 3 lb/ton estimated as an average by the PHS.[7] The median value is 2.75 lb/ton.

A comparison of Figures V–1 and V–2 shows that the emissions from small units are lower by a fraction of seven. Part of this difference is attributable to the differences in the refuse compositions used in the PHS tests from that for a typical municipal refuse and part is due to the larger gas convection currents expected in larger units. These effects will be discussed in greater detail in the following sections. It appears clear, however, that *numerical values* for emission rates in small units are not comparable with those of larger plants.

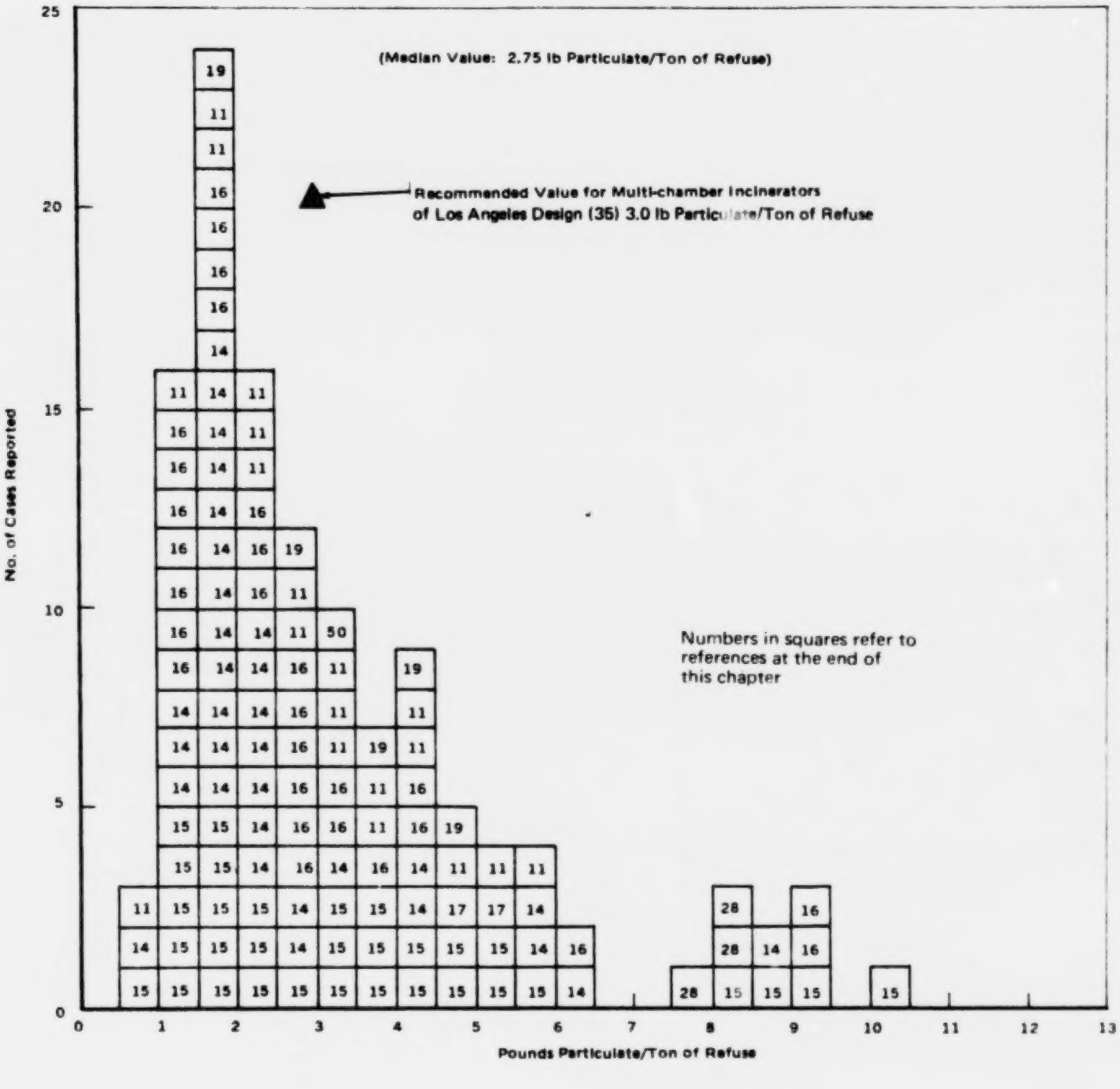


FIGURE V–2 HISTOGRAM OF PARTICULATE FURNACE EMISSION RATES (Capacity<10 TPD)

### 3. Effect of Design and Operational Variables on Emission Factors

The wide spread in emission rates in Figures V–1 and V–2 is a consequence of the variation in design and operation of the various incinerators tested and in the composition of the refuse burned. An appreciation for the factors that determine particulate emission and for their relative importance may be gained by considering the three mechanisms mainly responsible for the emission:

- The mechanical entrainment of particles from the burning refuse bed;
- The cracking of pyrolysis gases; and
- The volatilization of metallic salts or oxides.

The first of these mechanisms is favored by refuse with a high percentage of small particle size, low density ash, by residue or residue geometry favoring entrainment (plates), by high underfire air velocities, or by other factors that induce a high gas velocity through the bed. The second mechanism is favored by refuse with a high volatile content producing pyrolysis gases with a high carbon content and by conditions above the fuel bed that prevent the burnout of the coked particles formed by the cracking of the volatiles. The third mechanism is favored by high concentration of metals that form low melting point oxides and by high temperatures within the bed.

The detailed description of the fly ash composition and the effect of operating and design variables to be presented in the next section will be useful in evaluating the relative importance of the different mechanisms.

#### a. Refuse Composition

*(1) Ash Content.* Ash particles may be entrained when the velocity of the gases through the fuel bed exceeds the terminal velocity of the particles. Undergrate air velocities typically vary from a minimum of 10 SCFM/sq ft of grate area to 100 SCFM/sq ft. Based on the terminal velocity of ash particles (Figure V–3), it is therefore expected that particles up to 70$\mu$ (equivalent diameter) will be entrained at the lowest velocities and up to 400$\mu$ at the highest. The postulated mechanism of particulate entrainment is supported by the observed range of particle sizes of fly ash, the increases in particulate emission with increases in refuse ash content, the increases in particulate emission with undergrate air velocity, and the similarity in the chemical analyses of fly ash and those of the ash

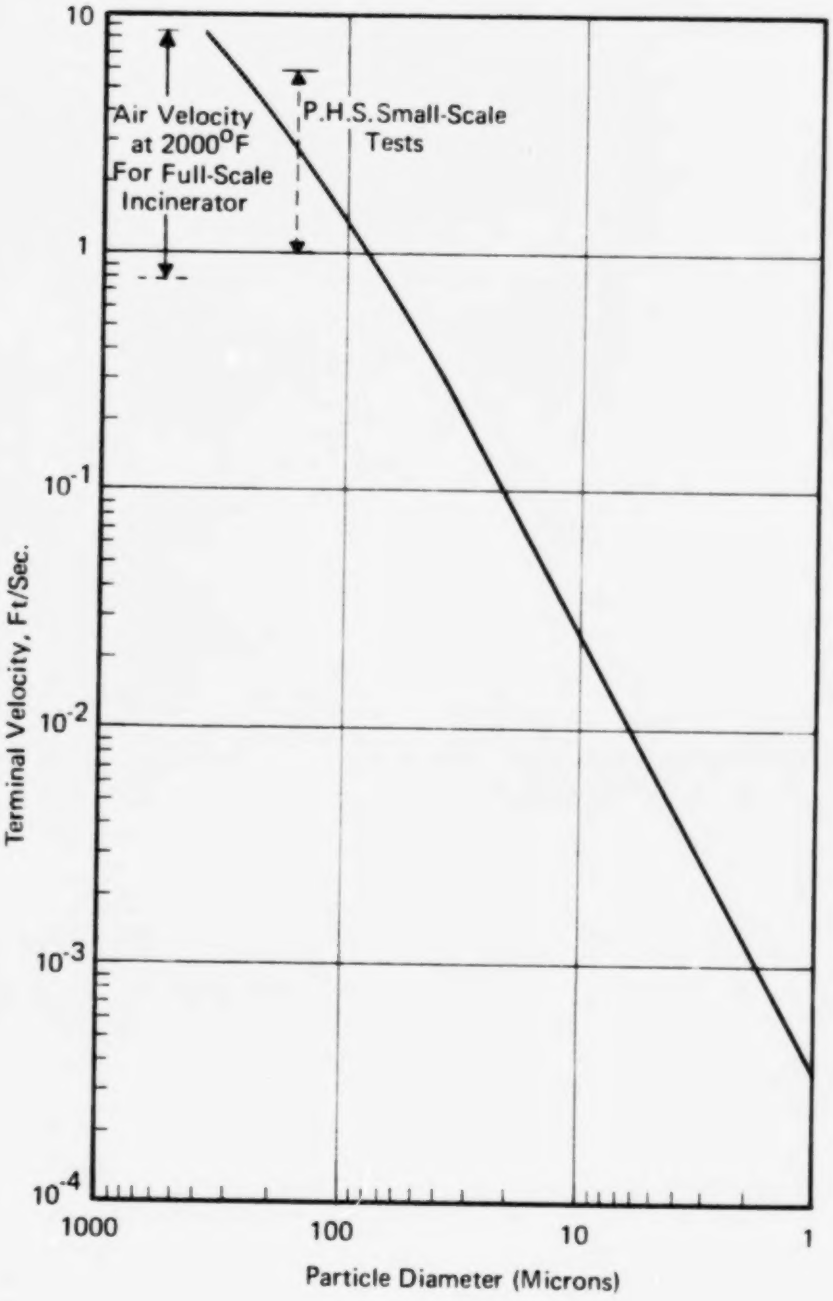


FIGURE V–3 PARTICLE FLUIDIZATION VELOCITIES (Terminal Velocities)

of the principal constituents of refuse. The quantitative use of such predictions is uncertain, however, because of the effect of particle shape on both entrainment mechanisms and on particle size measurement results.

The particle size distributions of fly ash (Figure VII–1 and Table VII–4 in Chapter VII) show 70 weight percent of the particles are smaller than 250μ. This is consistent with the calculations of terminal velocities. The data available, however, are insufficient to test the expectation that the maximum particle size of the fly ash emitted increases with undergrate air velocity.

The dependence of particulate emission on the ash content of refuse is most striking. The very high ash content of refuse in Germany, particularly during the winter in areas in which a high fraction of the residential furnaces are coal-fuel, accounts for the spread towards high emission rates in Figure V–1. The correlation of furnace emission rates with ash content of refuse is demonstrated by the data abstracted in Table V–3 from articles by Eberhardt and Mayer[17] and by Nowak[18]. The refuse ash content and furnace emission rates in January are greater than the corresponding values in August by factors exceeding four and six, respectively. The percentage of the refuse ash that is carried over with the combustion gases, however, varies much less with season: ranging from 10 to 15%. The variation in the percentage of the refuse ash carried over would be smaller if the value were based on the fine particle fraction of the ash in place of the total ash content, but the percentage of the fine ash carried over would, of course, be larger. The fraction of refuse ash falling into the "fine particle" category is difficult to define precisely. As a starting point, however, the glass and metal components of refuse ash can be excluded. It is interesting to note that the value reported[33] for the particulate emission for a chain grate stoker burning coal corresponds to a little over 20% of the ash content of the coal, a value not very different from the range found for refuse.

Additional evidence of the effect of ash content on particulate is provided by the Public Health Service studies on an experimental incinerator.[15] Tests were conducted first with a synthetic refuse consisting of newspaper, cardboard, wood and potatoes, and then repeated with a high ash paper substituted for the newspaper. The ash contents have been here estimated to be 2.0 weight percent for a 25% moisture synthetic refuse and 7.5 weight percent for the case in which high ash paper is substituted for the refuse. These estimates were obtained from the percentages of the different components reported by the P.H.S. and from the ultimate composition of typical refuse components reported by Kaiser.[19, 20] The results summarized in Table V–4 show that for large percentages of underfire air the percentage of the refuse ash carried over in the combustion gases is approximately the same for the two different fuels and ranges from 8 to 22 with a maximum value a little greater than that found in European practice. However, at

## TABLE V-3

## SEASONAL VARIATION IN REFUSE ASH CONTENT AND FURNACE EMISSION RATE

| Month | Refuse Ash Content | Refuse Heating Value (Btu/lb) | Furnace Emission Rate (grams/Nm$^3$) | % Refuse Ash Emitted |
|---|---|---|---|---|
| January | 44.5 | 2,160 | 15 | 14 |
| February | 38 | 2,360 | 12.8 | 15 |
| March | 30.5 | 2,560 | 9.3 | 13 |
| April | 27 | 2,640 | 7 | 13 |
| May | 22 | 2,760 | 5.3 | 12 |
| June | 18 | 2,970 | 4 | 13 |
| July | 12.5 | 3,000 | 2.3 | 10 |
| August | 10.5 | 2,850 | 1.9 | 10 |
| September | 14.5 | 2,840 | 2.7 | 10 |
| October | 26 | 2,600 | 5.7 | 11 |
| November | 35.5 | 2,430 | 10 | 13 |
| December | 43 | 2,320 | 13.7 | 14 |

**Source:** Data for incinerators in Germany from References 17 and 18

## TABLE V-4

## EFFECT OF ASH CONTENT ON EMISSION RATES[15]

| Refuse Ash Content (%) | Underfire Air % of Total | Emission Rate lb/ton | % Refuse Ash Emitted |
|---|---|---|---|
| 2.0 | 15 | 1.14 – 4.37 | 2.74 – 11 |
| 2.0 | 60 | 3.10 – 8.90 | 7.75 – 22 |
| 7.5 | 15 | 1.47 – 3.72 | 1.0 – 2.5 |
| 7.5 | 60 | 13.2 – 31.6 | 8.8 – 21 |

low underfire air rates, the percentage of the fly ash carried over is much smaller and better agreement is found between the absolute emission rates for low and high ash content fuels than between the corresponding percentages of ash carried over.

These findings show that the ash content of the refuse is a major factor in determining emission rates, and that the percentage of the ash carried over ranges mostly between 10 and 20% of the total. The actual percentage carried over for a particular incinerator will, of course, depend on other factors such as the underfire air rate. Consideration of the particle terminal velocities indicates that the above conclusions apply only to fine-particle ash (finer than 400μ).

The above conclusion, that approximately 10-20% of the fine ash content of refuse is carried over, may be tested by application to the typical municipal composition described in Appendix C. A ton of refuse (as received) yields 109 lb of ash, excluding the metal and glass components and thus would be expected to yield a furnace emission of 11 and 22 lb/ton. This is in fair agreement with the middle range of emission rates for U.S. incinerators; particularly since combustible particulate emissions must be added to the 11-22 lb/ton mineral particulate emission rate for comparability. In addition, the composition of the mineral portion of the fly ash may be calculated from the composition of the ashes of the refuse constitutents assuming that no selective entrainment occurs. The composition of fly ash so estimated is compared in Table V-5 with the analyses of the combustible free fly ash collected in three New York incinerators,[1] and the average analysis of 25 slag samples obtained[20] from 9 incinerators in New York, New Jersey and Connecticut. The agreement between the data on fly ash composition and the values computed from the ash of a typical refuse is satisfactory, the major differences being the higher value of iron, aluminum, and sulfur oxide found in the ash collected in the New York incinerators. Oxidation of most of the aluminum foil and part of the iron refuse is a possible explanation for the high percentages of aluminum and iron oxides in the fly ash. The high sulfur content may be contributed by calcium sulfate in wall board or plaster. Alternatively the capture of sulfur oxides by alkali oxides, as postulated by Kaiser[38] may be the predominant cause. From these results, the ash entrainment mechanism appears to be the dominant one in controlling mineral particulate emissions from municipal incinerators.

*(2) Volatile Combustible Content of Refuse.* The large volumes of combustible-rich pyrolysis gases generated during the incineration of refuse with a high volatile content tend to result in particulates with a high fraction of soot and other combustibles. Sooting tendencies are particularly high for pyrolysis gases with a high carbon content. Tests carried out by the PHS[16] on an experimental incinerator, using asphalt-saturated felt roofing as fuel, resulted in emission rates ranging from 2.6 to 84 lb/ton of refuse, and with an average value of 30.5 lb/ton.

## TABLE V-5

## COMPOSITION OF INORGANIC COMPONENTS OF FLY ASH

| Component | Computed For Typical Refuse | NYC Incinerators[1] | | Average[20] Analysis Of 25 Slag Samples |
|---|---|---|---|---|
| | | 73rd St. | So. Shore | |
| $SiO_2$ | 53.0 | 46.4 | 55.1 | 44.73 |
| $Al_2O_3$ | 6.2 | 28.2 | 20.5 | 17.44 |
| $Fe_2O_3$ | 2.6 | 7.1 | 6.0 | 9.26 |
| CaO | 14.8 | 10.6 | 7.8 | 10.52 |
| MgO | 9.3 | 2.9 | 1.9 | 2.1 |
| $Na_2O$ | 4.3 | 3.0 | 7.0 | 8.14 |
| $K_2O$ | 3.5 | 2.3 | – | – |
| $TiO_2$ | 4.2 | 3.1 | – | – |
| $SO_3$ | 0.1 | 2.7 | 2.3 | 3.69 |
| $P_2O_5$ | 1.5 | – | – | 1.52 |
| ZnO | 0.4 | – | – | 1.54 |
| BaO | 0.1 | – | – | – |
| | 100.0 | | | |

The average combustible content of the particulate was 87.7%. By contrast, a 25% moisture synthetic fuel incinerated under similar conditions resulted in emission rates ranging from 1.1 to 9.4 lb/ton with an average value of 4.1 lb/ton. If, however, only the ash content of the particulates for the high volatile fuel is considered, the emission rate is found to range from 1.0 to 9.4 lb/ton with an average value of 3.0 lb/ton. It should be noted that the total ash content for both the 25% moisture synthetic fuel and the asphalt-saturated felt roofing was 2.0%, and that it would therefore be expected that if the mechanism of fly ash emission is one of physical entrainment, then both fuels would give similar results on a combustible-free basis. Figure V-4 supports this conclusion since it shows that the PHS correlation[28] of the effect of underfire air velocity on particulate emission obtained with a synthetic refuse correlates the data on high volatile fuels after the large combustibles fraction (0.87 on the average) has been subtracted. Additional evidence of the importance of ash content is provided in Reference 15 in which the data on emission rate using the cellulosic fuels were found to give a better correlation with underfire air rate when plotted on a combustible-free basis. The combustible portion of the particulates is probably formed by the cracking of products of pyrolysis above the fuel bed.

That pyrolysis and coking are the mechanisms of formation of the combustible portion of fly ash is supported by the data on fly ash analysis. Values of the combustible content of fly ash collected in the APC device or emitted from the stack are summarized in Table V-6 for a number of furnaces. It will be noted that the organic content of the fly ash emitted from the stack is much higher than that in the fly ash collected, when both are reported, supporting the conclusion that the organic content consists of finer particles, such as soot.

From the very limited data in Table V-6, combustibles are shown to account for approximately 22% by weight of the particulate emitted from the furnace. It is felt, however, that this average value is in error. Let us assume that the particulate leaving the furnace is 15% combustible. In view of the efficiency range of the incinerators shown in Table V-6, one could expect approximately 70% collection efficiency for the coarse mineral particulate and 20% for the fine particle-size combustible particulate. The effluent particulate flow, with these assumptions, would show an overall 63% average efficiency and would produce a stack particulate with 32% combustible content. The same assumptions assuming 22% combustible in the furnace particulate yield a stack particulate with a 43% combustible content. Based on this reasoning, therefore, it will be assumed that furnace particulate is 15% combustible and 85% mineral material.

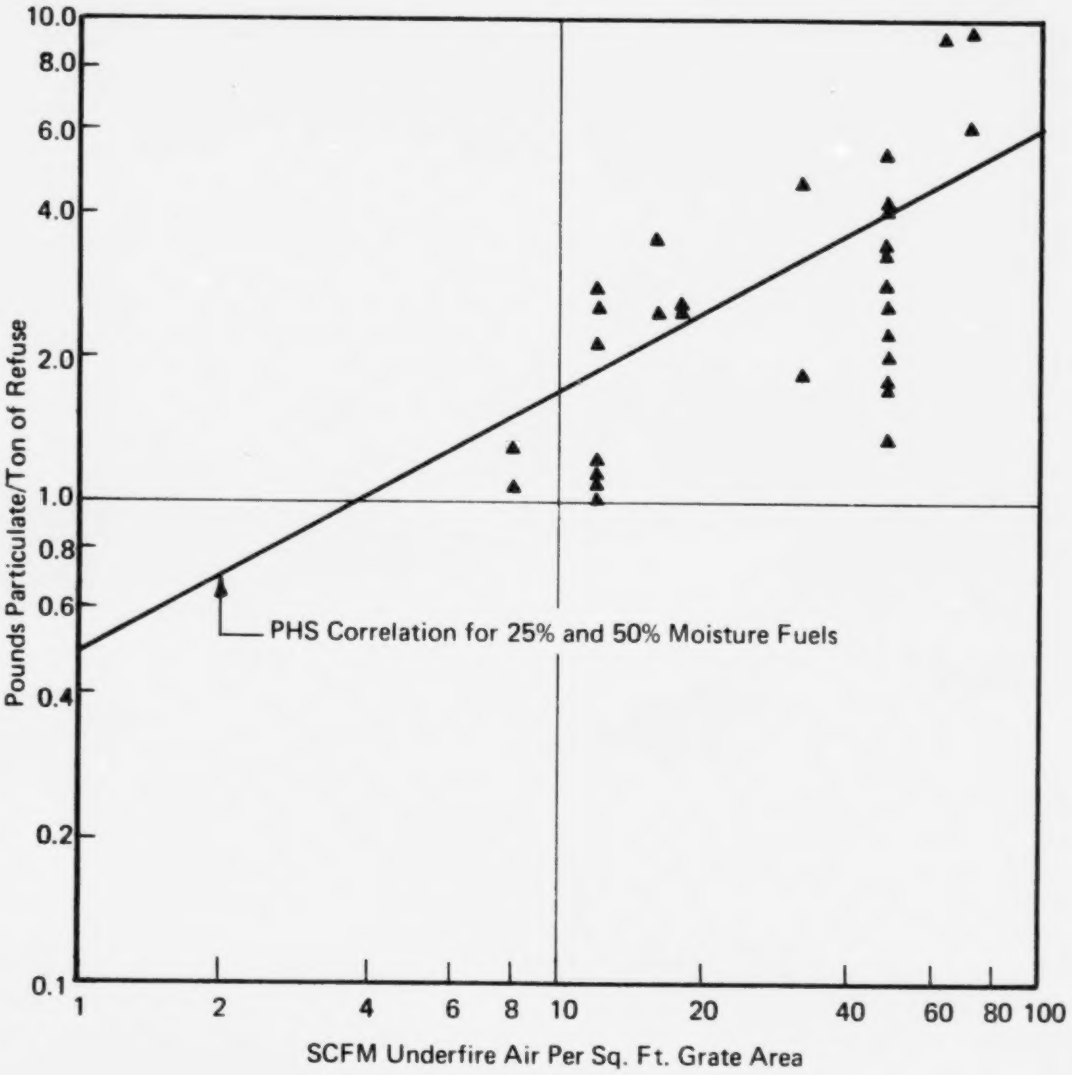


**FIGURE V–4** EFFECT OF UNDERFIRE AIR RATE ON EMISSION FACTORS. DATA POINTS CORRESPOND TO ASH CONTENT OF PHS EMISSION RATES FOR HIGH VOLATILE FUELS.

## TABLE V-6

## COMBUSTIBLE CONTENT OF FLY ASH

| Plant No.* | Combustible In Ash Emitted From Furnace (%) | Air Pollution Control System Overall Particulate Collection Efficiency (%) | Combustible In Ash Collected (%) | Combustible In Ash Emitted From Stack (%) |
|---|---|---|---|---|
| 40 | | 85 (est.) | | 39.7 |
| | | | | 43.3 |
| 22 | | 65 (est.) | | 29.6 |
| | | | | 15.8 |
| | | | | 30.8 |
| | | | | 28.3 |
| | | | | 26.5 |
| | | | | 32.2 |
| 57 | | 99 (est.) | 5.7 | 34.3 |
| | | | 6.7 | 25.1 |
| 76 | | 25 (est) | 0.6 | 10.4 |
| 95 | | 25 (est) | | 14.5 |
| 78 | 18.5 | ? | | |
| 79 | 8.2 | ? | | |
| 80 | 30.4 | ? | | |
| 89 | 6.58 | 99.7 | 6.58 | |
| | 6.63 | 99.7 | 6.63 | |
| 10 | 27 | 73 | 22 | 40 |
| | | | | 32 |
| | | | | 35.7 |
| | | | | 39.5 |
| | | | | 48.3 |
| | | | | 39.9 |
| | | | | 46.6 |
| | | | | 41.8 |
| | | | | 34.5 |
| | | | | 45.2 |
| | | | | 49.2 |
| | | | | 36.9 |
| | | | | 31.0 |

* Reference Table J-1, Appendix J

## TABLE V-6 (Continued)

| Plant No.* | Combustible In Ash Emitted From Furnace (%) | Air Pollution Control System Overall Particulate Collection Efficiency (%) | Combustible In Ash Collected (%) | Combustible In Ash Emitted From Stack (%) |
|---|---|---|---|---|
| 10 | | | | 37.8 |
| | | | | 38.0 |
| | | | | 39.1 |
| | | | | 40.5 |
| | | | | 15 |
| – | – | – | 0.5 | 15 |
| 20 | 37 | 62 | 5.9 | 57 |
| | 40 | 64 | 10 | 57 |
| | 24 | 54 | 8.4 | 37 |
| | | | | 46.5 |
| | | | | 68.1 |
| | | | | 53.4 |
| | | | | 61.5 |
| | | | | 45.1 |
| | | | | 28.7 |
| 6 | | 50 (est.) | | 41.95 |
| | | | | 29.6 |
| | | | | 24.15 |
| | | | | 27.90 |
| | | | | 31.95 |
| | | | | 32.88 |
| 1 | | 65 (est.) | | 51.42 |
| | | | | 44.38 |
| | | | | 59.34 |
| | | | | 42.43 |
| | | | | 37.45 |
| 10 | | 65 (est.) | | 18.5 |
| | | | | 12.5 |
| | | | | 15.5 |
| 103 | | ? | | 27.5 |
| 7 | | ? | | 13.9 |
| 91 | | 70 (est.) | | 5.6 |
| | | | | 4.0 |
| | | | | 2.5 |
| | | | | 3.6 |
| | | | | 6.0 |
| | | | | 3.2 |
| Average of All Data Points | 7.30 | 22.0 | | |
| Standard Deviation | 5.97 | 12.9 | | |

* Reference: Table J-1, Appendix J.

The potential for reducing the combustible content of the particulate emission by better control of the temperature and mixing in the furnace can be evaluated by examining the kinetics of combustion of carbonaceous particles. The burning rate of carbon particles has received much study,[22] and for spherical particles can be approximated by

$$q = \frac{P_{O_2}}{1/K_s + 1/K_d} \qquad (1)$$

where q is the rate of carbon consumption in grams/(cm$^2$)(sec), $P_{O_2}$ the particle pressure of oxygen in atmospheres, $K_s$ the kinetic constant for chemical reaction, and $K_d$ the diffusional rate constant. For carbon, $K_s = 0.13 \exp [(-35{,}000/R)(1/T-1/1000)]$ where T is in °K. For small particles, the Sherwood Number approaches 2.0, and

$$K_d = 2.38 \times 10^{-5} \left[\frac{T}{d}\right]^{0.75} \qquad (2)$$

where d is the particle diameter in centimeters, and T is in °K. For an assumed combustible particle specific gravity of 2.0, and burnout at constant temperature and oxygen concentration, the time $t_b$ required to completely burn out soot particles calculated from the above is given by

$$t_b = \frac{1.0}{P_{O_2}} \left[ \frac{d}{\exp\Bigl[(\frac{-35{,}000}{R})(\frac{1}{T} - \frac{1}{1000})} + \frac{d^2}{4.76 \times 10^{-5}\, T^{0.75}} \right] \qquad (3)$$

Thus, for an incinerator operating at 2000°F with 100% excess air,

$$t_b = 11.1 \quad \frac{d}{0.026} + \frac{d^2}{0.011} \Bigr] \qquad (4)$$

the burnout time for 2-, 20- and 200-micron particles can be shown to be slightly under 0.1, 1.0, and 10 seconds, respectively. The residence time in conventional combustion chambers is in the range of 1 to 4 seconds which is sufficient at 2000°F to burn out all carbonaceous particles below 24 to 94 microns in diameter. The high concentration of organic material in the emission from the stack must therefore be a consequence of poor mixing in the combustion chamber, of the formation of combustible particles larger than the 24-$\mu$ to 94-$\mu$ size range that could be expected to burn out, or of the rapid cooling of the combustion gases by large amounts of excess air.

Figure V-5 illustrates how increases in excess air, with the concomitant decrease in adiabatic flame temperature, greatly increase the time required to burn out the particles. With 300% excess air and a relatively long residence time

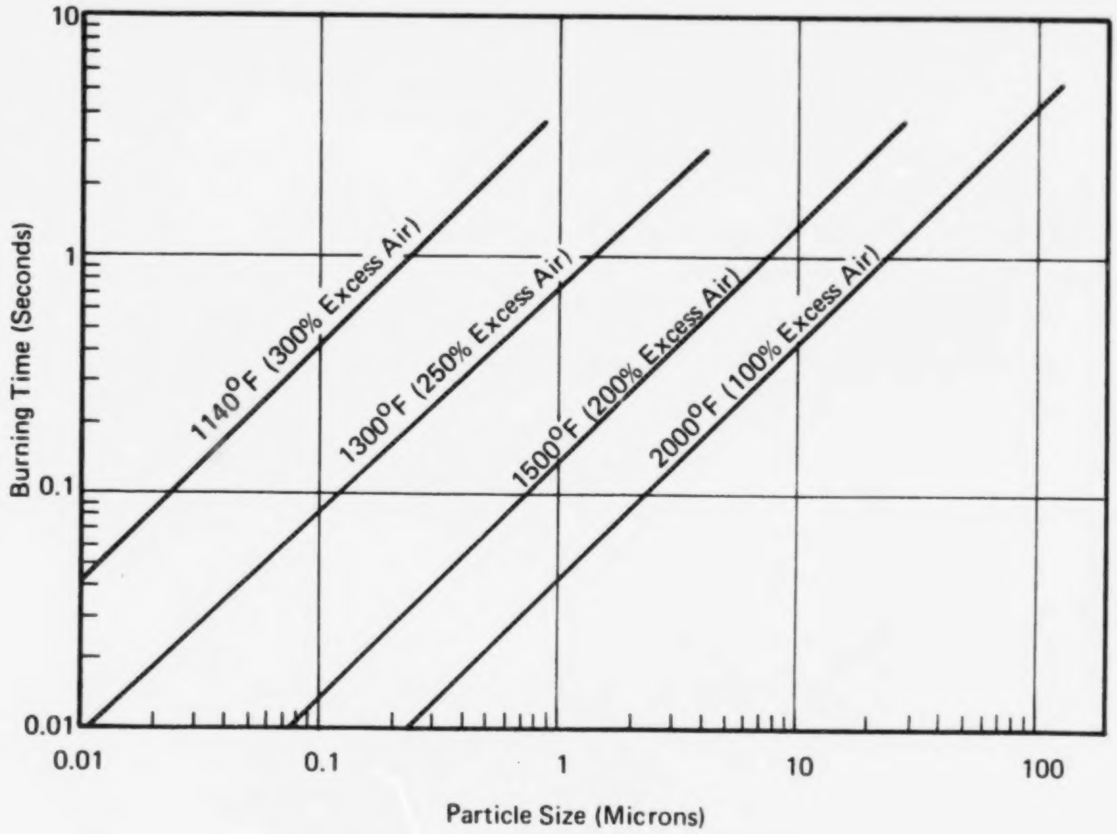


FIGURE V–5 TIMES REQUIRED FOR COMBUSTION OF CARBONACEOUS PARTICLES

of 4 seconds in the combustion chamber it is estimated that only particles with diameters under a micron would be burned out. From these considerations it appears that the presence of significant amounts of combustible in the stack gases is probably a consequence of either a rapid quenching of the flue gases by the introduction of large amounts of excess air into the combustion chamber or of poor mixing between the pyrolysis products having the fuel bed and the combustion air.

The importance of good overbed mixing has long been recognized as a very effective means for the reduction of smoke emission from coal stokers. Mixing has been achieved by use of air and steam jets.[23] The design and placement of the jets, however, are critical. If the jets are positioned too high above the refuse bed, they will quench the flue gases rather than complete the combustion. Conversely, if positioned too low, ash material can be suspended from the refuse bed.

The early experience on the placement of overfire jets over coal beds has not been utilized fully in incinerator design.[24] More effective use of jets in incinerators can significantly reduce the combustible content of the emission and offers one of the less expensive methods of quickly improving the air pollution performance of existing units.

An excellent illustration of the stratification that can occur in incinerators is provided by Woodruff and Larson.[25] In a vertical cross section normal to the main flow direction they observed a 12-fold variation in concentration of particulates, a 2.7-fold variation in carbon monoxide concentration, and variations in oxygen concentration in the midsection of the secondary combustion chamber that ranged from zero to 9.5 percent. Examples of the segregation of the gases in a combustion chamber above a grate into a region containing combustible gases, but no oxygen, and a region containing oxygen, but no combustible gas, are provided by the Bureau of Mines studies[26] on experimental incinerators and by the studies on coal-fired stokers by Mayers.[27]

*(3) Volatilization of Metallic Salts.* Although a major fraction of fly ash from municipal incinerators appears to have been entrained from the fuel bed or formed by cracking of pyrolysis products, observed emission characteristics for small incinerators cannot be explained soley by an entrainment mechanism.[12,14] For example, the sizes of the particulate in the stack discharge data reported by Rose and Crabaugh[12] are mostly in the 0 to 5-micron range. Based on the physical shape as determined from microscopic examination and on chemical analyses of the noncombustible, they concluded that particulates were formed by volatilization and recondensation of metallic salts. This finding, however, is inconsistent with the data on large units for which particles of 0 to 5 microns usually constitute a small fraction of the total emission.

The temperature within a burning refuse bed can reach 2500-3000°F. At these temperatures, a number of metal salts (particularly those of the alkali metals) will vaporize or sublime. Therefore, it would appear that although volatilization of salts may be occurring in localized hot spots within the burning bed, the low concentration of these salts in refuse, the low frequency and/or intensity of the hot spots, condensation of the vapors within cooler regions of the bed, or other considerations prevent or attenuate emission. The contribution of metallic salt volatilization to the total furnace particulate emission rate thus appears small in municipal-scale incinerators but may be important in smaller units.

b. Underfire Air Rate

A systematic study by the PHS[15] of the effects of underfire air, secondary air, excess air, charging rate, stoking interval, and fuel moisture content on the emission rate from an experimental incinerator led to the conclusion that the velocity of the underfire air was the variable that most strongly influenced particulate emission rate. The data on 25% and 50% moisture fuel (about 2% suspendable fine ash) were correlated by

$$W = 0.48\ V^{0.548} \tag{5}$$

where W is the pounds of particulate emitted per ton of refuse burned, and V is the underfire air rate in SCFM per square foot of grate area. This correlation is shown as the solid line in Figure V-6. The range of undergrate velocities studied ranged from 2 to 100 SCFM/sq ft of grate area. Subsequent field evaluation by the PHS[28] of emission rates from municipal incinerators indicated that the effect of underfire air rate was less pronounced than that predicted by the above equation and suggested that, for the two municipal incinerators tested, the effect was small for undergrate velocities below 35 to 40 SCFM/sq ft of grate area, but significant above that rate.

Walker and Schmitz,[29] however, correlate their test results on three municipal incinerators with the relationships developed by the PHS on the experimental incinerator. The refuse burned during these tests would be expected to contain about 5% fine ash based on the average refuse composition developed in Chapter IV. A representative set of the PHS data on the experimental incinerator is compared with the field tests and Walker and Schmitz data in Figure V-6. The spread in the data is not surprising in view of probable differences in refuse composition, furnace size and other variables.

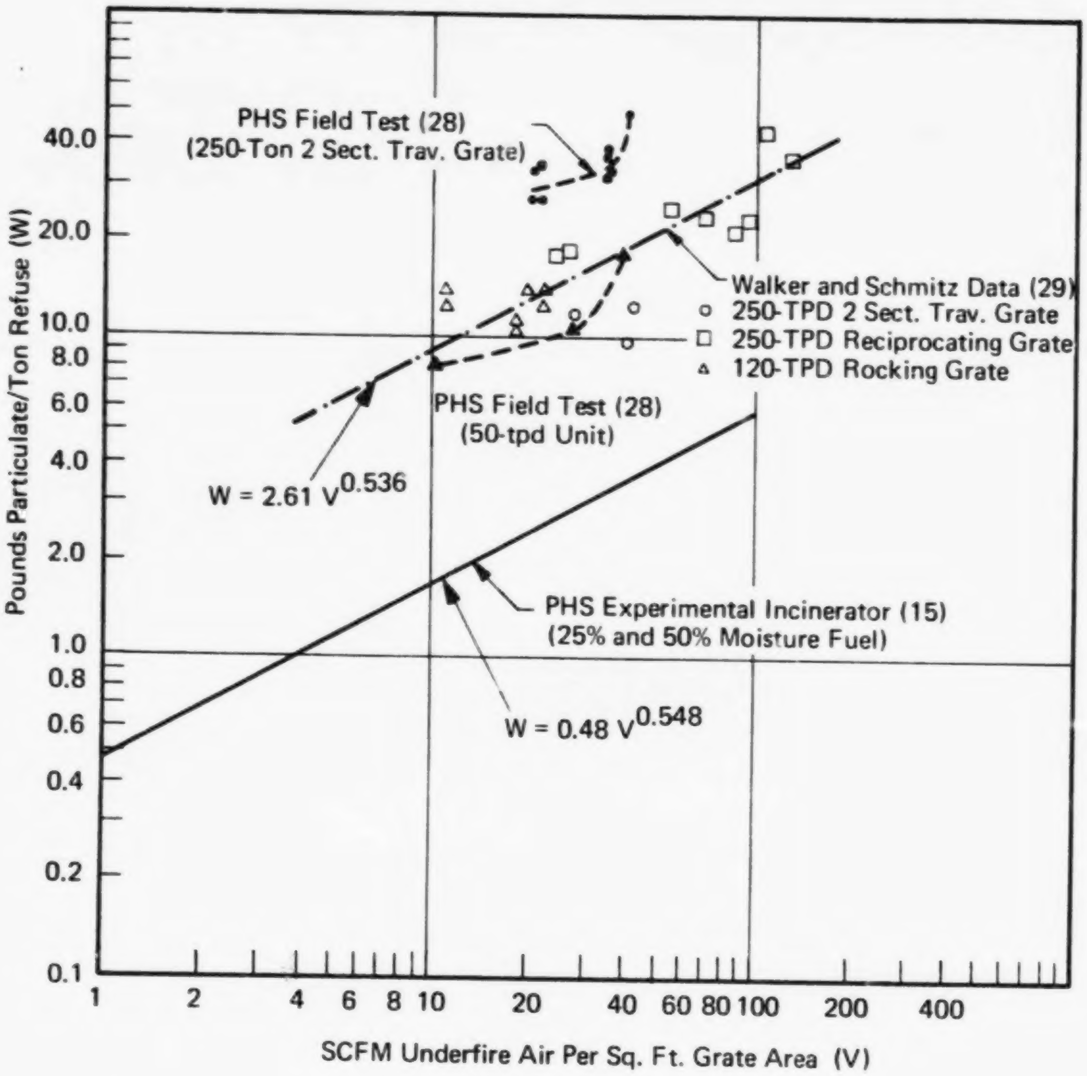


FIGURE V–6 EFFECT OF UNDERFIRE AIR RATE ON FURNACE EMISSION

The upper line (-·-·-), for municipal-scale incinerators in Figure V-6 is described by

$$W = 2.61\ V^{0.536} \qquad (6)$$

It is significant that the dependence of emission rate on undergrate air rate is similar to that shown in the small-scale tests (Equation (5)). It would appear from these data that the particulate emission rate is (approximately) related to the square root of undergrate air rate for most incinerator sizes and types. The wide variations in indergrate air use between different incinerators, therefore, partially accounts for the scatter seen in collections of particulate emission data (e.g., Figure V-1). Unfortunately, however, such engineering data are seldom measured or reported during emission testing.

The dependence of emission rate upon unit size shown in Figure V-6 is strong: between small (3 TPD) and large (120 TPD) plants, the emission rates vary five-fold at similar undergrate air rates. A portion of the variation is probably due to differences in the fine ash content of the refuse burned (2% and 5% for the small and large units respectively). The remaining two-fold difference may be related to size effects as discussed below. Within the scatter of the data, however, over the two- to three-fold range of furnace capacities typical of most municipal incinerators, the quantitative relationship between emission and undergrate air rate appears substantially unchanged. Equation (6), therefore, represents a useful tool for engineering evaluations. Clearly, additional data are required to confirm this relationship.

Although the data in Figure V-6 demonstrating the increase of particulate emission with underfire air are limited, supporting evidence for the trend observed is provided by numerous observations of this effect in the literature.[5,12,25,30] Additional data supporting the conclusions derived in the literature are those on Plant No. 76 (see Table J-1, Appendix J). The tests of this furnace showed that the emission increased 59% as the underfire air rate was increased from 50% to 100% of the total air, but that decreases in excess air from 50% to 20% resulted in a 44% increase in emission. The anomalous behavior at 20% excess may be attributed to the very poor burning characteristic and the extensive hand-stoking required at the low excess air limit.

Although reduction in the undergrate air rate can reduce the particulate emission from the furnace, there is usually an attendant reduction in burning rate.[12,28] An economic analysis of the trade-off between furnace burning capacity and air pollution control equipment costs would be needed for optimization. There is, of course, a minimum undergrate air requirement necessary to protect the grate. Also, a great reduction in undergrate air would greatly increase the amount of unburned refuse pyrolysis products leaving the top of the bed. Unless intense overfire mixing were obtained, several-fold increases in combustible pollutant emission would result. No data were found, however, to quantify this relationship.

c. Incinerator Size

Increasing the size of incinerator units from 3 to over 100 TPD was shown (in Figure V-6) to result in higher emission rates, but the effect of size on emission factors has not been quantitatively established over the more limited size range of municipal furnace units (50-300 TPD). Part of the increase is due to the higher burning rates (lb/hr-sq ft of grate), and hence higher underfire air rates associated with large units. However, if emission on large and small units are compared at equal underfire air velocities, a residual effect of size is found. Possibly the higher emission rates for the larger sizes are a consequence of the higher natural convection currents encountered in larger units.

From dimensional analysis, it can be shown that for a buoyancy driven flow the velocity V of the induced air is proportional to $\sqrt{L\Delta\rho/\rho g}$, where L is a characteristic length of the combustion chamber, $\Delta\rho$ is the difference in density between the colder entrained gases and the hot combustion products, and $\rho$ is the mean density of the combustion products, and g is the gravitational acceleration. Entrainment of particulate by buoyancy driven flows will, therefore, increase with furnace size and flame temperature.

d. Burning Rate

For reasons similar to those presented in Section c above, it is expected that higher emission rates will be encountered at higher burning rates. Rehm[3] cites that reductions in rate of burning to 75% of rated capacity have shown as much as 30% reduction in furnace emission from that at full capacity; however, insufficient data are available for a quantitative relationship to be established as important variable changes specified. A simple reduction in undergrate air rate to match the reduced burning rate, for example, would make a 15-20% particulate reduction as suggested by Equation (6).

e. Combustion Chamber Design

Practically the only data in this area are provided by the studies on small incinerators in Los Angeles County. From these data, it was concluded[12] that the emission from small units could be reduced substantially by the use of multiple chambers and by the use of a low arch. The emission in these tests primarily consisted of particles under $5\mu$ in size, and there is uncertainty concerning the applicability of the results or the design parameters developed to large municipal incinerators. The need for multiple combustion chambers for large units, for example, will depend mainly on the adequacy of mixing in the primary chamber.

### f. Grate Type

Stoking has been observed to increase particulate emission rates. This is particularly evident from the tests on Plant No. 76 and the PHS field tests[28] on the effect of underfire air rate, where the stoking required at the lowest air rates led to a significant increase in emission. Walker and Schmitz,[29] however, report results that suggest that the effect of grate design on emission is secondary to the effect of underfire air rate or refuse ash content. The results of their tests on the emission from furnaces operating with a two-section traveling grate, a rocking grate, and a reciprocating grate, are shown on Figure V-6. They concluded that the differences in emission were primarily due to the differences in underfire air velocities used in the different units. The conclusion reached by Walker and Schmitz[29] may be correct in the context of their experiments: within the scatter of their data, no clear dependence on grate type was visible. However, the following considerations encourage one to seek a relationship between grate type and pollutant emissions:

- The grate type (plus charging method – batch or continuous) often defines the general design of the total furnace system. The furnace design would be expected to affect mixing patterns, flue settlement, etc.

- Specific undergrate air flows are suggested by the grate manufacturer. Although wide variations from the suggested settings occur in practice, it is reasonable to expect that some "clustering" of operating points around the suggested value will occur for any specific grate system.

- The above-mentioned stoking intensity (causing attrition of the residue) varies widely between systems and would be expected to increase the fraction of the ash material in the size range capable of suspension and to expose more of this suspendable material to the undergrate air flow.

- The percent open area of the grate surface controls the amount of ash material dropping through the grate (siftings). This grate parameter varies widely (2% to 30%). Since the small particle size ash is "lost" from the bed by this mechanism, less is available for suspension in the undergrate air flow.

Thus, grate type, though not in itself defining the emission rate of pollutants, may be viewed as an integral variable, reflecting the effect of a number of parameters. Since most of these more fundamental parameters are neither known for a given set of emission data, nor is their quantitative relationship to emission understood, grate type is a useful, though not rigorous, variable to reveal differences in emission rate between units.

In order to provide allowance for grate type in the furnace emission factors, the data on the different types of units from Table J-1, Appendix J, were compiled separately in Figure V-7. The emission rates from reciprocating grate stokers are seen to be significantly higher than those from other grate types. It is probable that the higher rates in the reciprocating grate units are due to a combination of greater stoking intensity and higher underfire air rates than the other units. Another factor is the difference in grate openings which can result in large differences in the amount of fine ash that can sift through the grate.

The sample of data on several of the units was so small that it was deemed advisable to select the median rather than the average for each grate type since the average for a small sample can be so heavily biased by one large number. The median total particulate emission rates are shown in Table V-7. In order to differentiate between mineral and combustible particulate, consideration must be given to the combustion characteristics of the various grate/furnace types.

### TABLE V-7

### MEDIAN TOTAL PARTICULATE* FURNACE EMISSION FACTOR SUMMARY

| Grate/Furnace Type | Median Emission Factor |
|---|---|
| 1. Batch Feed | |
| Rectangular Cell | 23 lb/ton of as-fired refuse |
| Circular | 12 lb/ton of as-fired refuse |
| 2. Continuous Feed | |
| Traveling Grate | 15 lb/ton of as-fired refuse |
| Rocking Grate | 16 lb/ton of as-fired refuse |
| Reciprocating Grate | 33 lb/ton of as-fired refuse |

*Includes mineral and combustible particulate

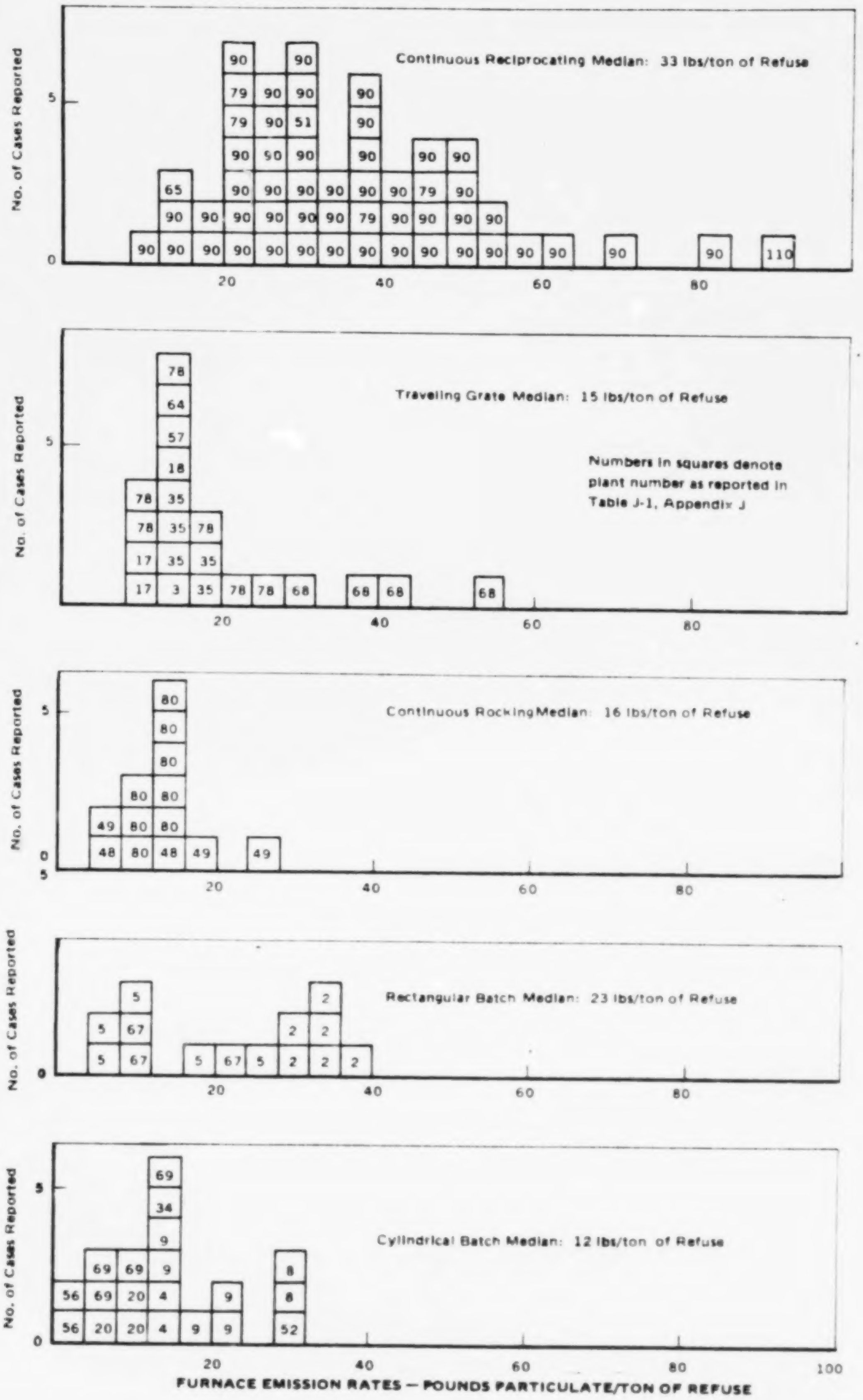


FIGURE V–7 HISTOGRAM SHOWING EFFECT OF GRATE AND FURNACE TYPE ON TOTAL PARTICULATE FURNACE EMISSION RATE

g. Mixing Effects on Combustible Pollutants

The reduction in combustible solid and gaseous pollutants within an incinerator is primarily a function of the mixing processes within the system. In all realistic cases, the bulk flue gas temperature and the calculated average gas residence time within the furnace are more than adequate to assure complete combustion. Consideration of these facts suggests that a parameter could be defined which would characterize the completeness of mixing within the furnace. Such a parameter would reflect the integrated effects of stratification, the "burst" of combustible pollutants emitted following batch charging, mixing in the furnace and in flues, the adequacy of design and operation of overfire jets, etc. Because of its complexity, such a parameter cannot be easily defined or evaluated by engineering analysis but would arise from engineering judgment based on review of data and on qualitative evaluation of observations of incinerator and other furnace systems.

In order to quantify this mixing effect, we defined a mixing effectiveness factor, "MEF," such that for an "average" contemporary continuous-feed system, the MEF equals one; for "well-stirred systems," the MEF is less than one; and for "poorly-mixed systems," the MEF is greater than one. Based on the reasoning in part f regarding the utility of "grate type" as a variable parameter suggesting an overall furnace design and operating configuration, MEF values were designated for the set of incinerator types now in use and for use in projection of air pollution from incineration in the future, for several advanced concepts. The emission factor for a combustible pollutant for these incinerator types is calculated as the product of the MEF and the reference "average unit" emission factor. A summary of MEF values is presented in Table V-8.

TABLE V-8

MIXING EFFECTIVENESS FACTORS FOR MUNICIPAL INCINERATORS

| Furnace Type | Mixing Effectiveness Factor (MEF) |
|---|---|
| Batch-Fired, Rectangular Systems | 1.4 |
| Hearth Units | 1.4 |
| Batch-Fired, Cylindrical Systems | 1.2 |
| Continuous-Fired, Refractory Wall Systems (traveling, rocking, and reciprocating grates) | 1.0 |
| Slagging Systems – Type II | 1.0 |
| Continuous-Fired, Refractory Wall Grate-Kiln Systems | 0.7 |
| Water-Wall Boilers | 0.7 |
| Suspension-Firing Systems | 0.5 |
| Slagging Systems – Type I | 0.4 |
| Fluid Bed Systems | 0.1 |
| Pyrolysis Systems | 0.1 |

Slagging Type I incinerators are those using a shaft-type furnace or a specialized high-temperature combustion chamber (such as the American Thermogen or Dravo/FLK units) with a well-stirred, high-temperature reaction zone. The low MEF assigned to these units was based on recent tests of a shaft-type system for which low combustible gaseous pollutant concentrations were repeatedly observed. Type II slagging incinerators are those having considerable similarity to conventional continuous-feed incineration systems, where slagging is carried out as a separate operation (such as by residue fusion in an electric arc furnace). Low MEF values were assigned to boiler units reflecting the mixing induced in the convection tube section and the more intensive combustion design effort anticipated for such plants. Still greater mixing intensity is anticipated (low MEF) for suspension-fired boiler systems where additional turbulence is induced when the refuse is pneumatically fed. The low MEF assigned to fluid bed systems is a reflection of the very intense mixing characteristic of this unique combustion system. Although the gases leaving the pyrolizer furnace in systems based on the pyrolysis concept will contain enormous amounts of combustible, it is anticipated that this off-gas will be burned with very high combustion efficiency in ancilliary combustors, producing little combustible in the ultimate effluent stream (low MEF).

Although the specific MEF values chosen were not developed from actual measurement, and thus are speculative, they provide a useful instrument to indicate the impact of "typical" design and operating practices on emissions of combustible pollutants.

### 4. Combustible Particulate Emission Factors

In most cases, a differentiation is not made between the mineral and combustible fractions in reported measurements of the particulate in incinerator flue gas streams. As a result, the particulate emission factors, developed in parts 2 and 3 above, include contributions from both mineral and combustible material. Based on an evaluation of existing ash composition data (Table V-6), the average weight percent combustible in fly ash emitted from conventional incinerator furnaces is about 15%. From the data in Figure V-1, the median *total* particulate emission factor is 24 lb/ton of refuse. With the assumption of 15% carbon in furnace particulate, it is thus concluded that about 3.6 pounds of combustible particulate (carbon) are emitted per ton of refuse in an "average" incinerator.

It is suggested above (Page V-32) that combustible particulate emission is associated with coking of volatile material released from the refuse. It is further suggested here that the amount of combustible particulate formed is directly proportional to the fraction of the carbon in refuse which is volatilized (total carbon minus fixed carbon as measured by ASTM methods). By identifying this dependency, the effects of changing refuse composition can be estimated. Based on the standard refuse composition (Appendix C and Table IV-11), the volatile carbon content of typical refuse is 19.3% or 386 pounds per ton (25.6% total carbon and 6.3% fixed carbon). As an approximation, it was assumed that 1% of the volatile carbon in refuse (or 3.86 lb/ton) appears in the incinerator flue gas effluent as combustible particulate for typical incinerators. As described above, this value, multiplied by the mixing effectiveness factor (MEF) for different grate/furnace types, yields the combustible particulate furnace emission factors. A summary of these factors may be found in subsection I (Furnace Emission Factor Summary) below.

### 5. Mineral Particulate Emission Factors

Median total particulate furnace emission factors (mineral plus combustible) for conventional incinerators can be obtained from the histograms presented in Figure V-7 (Table V-6). The emission factor values from these histograms must be corrected for combustible content, however, to yield the mineral particulate portion. This calculation involves subtraction of the combustible particulate emission factor for each incinerator type (3.86 lb/ton times the appropriate MEF), from the total particulate emission factor from Figure V-7. The mineral particulate emission factors for waterwall boiler, grate-type incinerators were assumed the same as for their refractory construction counterparts. This assumes that approximately corresponding practices as regards undergrate air distribution will be followed in the boiler units. Although an insufficient number of such plants are now operating in the U.S. to establish any clear trends, it is reported that the waterwall unit in Norfolk, Virginia, frequently operates with 100% underfire air at 80% (overall) excess air. Under such conditions, particulate loadings somewhat higher than that indicated by the emission factor selected may be observed. No test data, however, are available.

The assumed mineral particulate emission factor for suspension burning units was based on review of emission characteristics for spreader stoker coal-fired boilers. It is expected that high particulate loading will be observed for these systems due to the pneumatic firing method. Emission factors for Slagging Type I units are based on test data on an American Thermogen shaft-type furnace[39] and reported characteristics of the Dravo/FLK incinerator.[40] In the case of the American Thermogen data, corrections are necessary to compensate for the high combustible content of the fly ash. Emission factors for Slagging Type II incinerators were taken as the unweighted average for the reciprocating, rocking and traveling-grate refractory wall systems, since Type II units are similar in design and operating practice to conventional plants. The high mineral particulate furnace emission factor assigned to the fluid bed unit is based on evaluation of the operating characteristics of similar fluid bed systems burning sewage sludge and other organic solids of mixed mineral and combustible content. Except for massive mineral residue, such as glass and metal, much of the ash in the refuse will be carried from the bed in the effluent flue gas stream. The low value assumed for the mineral particulate furnace emission factor for pyrolysis units reflects the low gas velocities characteristic of these processes in a kiln-type system and the filtering action of the incoming refuse bed in gas-producer-type systems. No data exist, however, to test these assumptions.

In the analysis above, it was suggested that the mineral particulate emission is related to the ash content of the refuse fired (excluding massive ash materials such as metal and glass). In order to identify the dependence of emission factor on refuse composition (necessary to determine the effects of changing refuse composition on future emissions), the emission factor can be presented on the basis of pounds of mineral particulate emitted per ton of glass and metal-free ash in refuse. Based on the refuse composition shown in Appendix C and Table IV-11, this ash comprises 108.8 lb/ton of refuse (5.44%).

The particulate emission factors are presented in subsection I (Furnace Emission Factor Summary) below.

## C. CARBON MONOXIDE EMISSION

Carbon monoxide (CO) is the most significant pollutant (on a weight basis) emitted from municipal incinerator furnaces. Of equal importance is the fact that existing APC systems do not significantly reduce this emission. The formation of CO in furnaces must be seen as a failure on the part of the combustion system to effect complete burn-out of the combustible gases rising from the refuse bed. Since APC systems do not offer a means to reduce the CO content of the flue gases, control and improvement of the combustion process in incinerator operation must be realized for effective air pollution abatement. The paragraphs below review the CO combustion process and summarize existing data to develop average furnace emission factors.

Carbon monoxide (CO) is produced by the incomplete combustion of the gaseous pyrolysis products or of the char in the refuse bed. The kinetics of the oxidation of carbon monoxide to carbon dioxide has been studied by several investigators and, although there are differences in the rate constant reported, a reasonable estimate can be made of the times required to complete the combustion. The rate constant reported by Hottell et al[31] will be used here to calculate the kinetics of oxidation of CO in the combustion chamber for the condition where the CO and air (oxygen) are intimately mixed. Their kinetic expression is given by

$$\frac{df_{CO}}{dt} = 12 \times 10^{10} \exp\left(\frac{-16,000}{RT}\right) f_{O_2}^{0.3} f_{CO} f_{H_2O}^{0.5} \left(\frac{P}{RT}\right)^{0.8} \qquad (7)$$

where $f_{CO}$, $f_{O_2}$, $f_{H_2O}$ are the mole fractions of carbon monoxide, oxygen, and water vapor, respectively, T the absolute temperature (°K), P the absolute pressure, t the time in seconds, and R the gas constant in cal/gm mole PK. For a simplified representation of the combustion chamber as an isothermal reactor, the reduction in concentration of carbon monoxide due to oxidation is given by

$$\frac{(f_{CO})\ \text{final}}{(f_{CO})\ \text{initial}} = e^{-Kt} \tag{8}$$

where t is the residence time, and

$$K = 12 \times 10^{10} \exp\left[-16{,}000/RT\right] f_{O_2}^{\,0.3}\ f_{H_2O}^{\,0.5}\ (P/RT)^{0.8}. \tag{9}$$

Values of K have been assessed for a typical refuse burned with different amounts of excess air and the results are presented in Table V-9.

The time required to reduce the carbon monoxide concentration from values of the order of 1% to negligible values (<1 ppm) will vary from less than a millisecond at 50% excess air to about 0.035 second at 300% excess air. This variation reflects the competitive effects of increased oxygen concentration and decreased temperature as the excess air increases. The residence times in the combustion chambers are usually significantly longer, and therefore little residual carbon monoxide would be expected *provided* that the air was intimately mixed (on a molecular scale) with the pyrolysis products. The presence of carbon monoxide in the stack gases is, therefore, attributed to poor mixing, or quenching of the gases by cold walls or improper addition of secondary air.

### TABLE V-9

### RATE CONSTANT FOR CARBON MONOXIDE OXIDATION

| Excess Air (%) | $f_{O_2}$ | $f_{H_2O}$ | T (°K) | K ($sec^{-1}$) |
|---|---|---|---|---|
| 50 | 0.05 | 0.16 | 1722 | 14,600 |
| 100 | 0.09 | 0.12 | 1372 | 5,300 |
| 200 | 0.13 | 0.08 | 1055 | 1,020 |
| 300 | 0.15 | 0.06 | 889 | 260 |

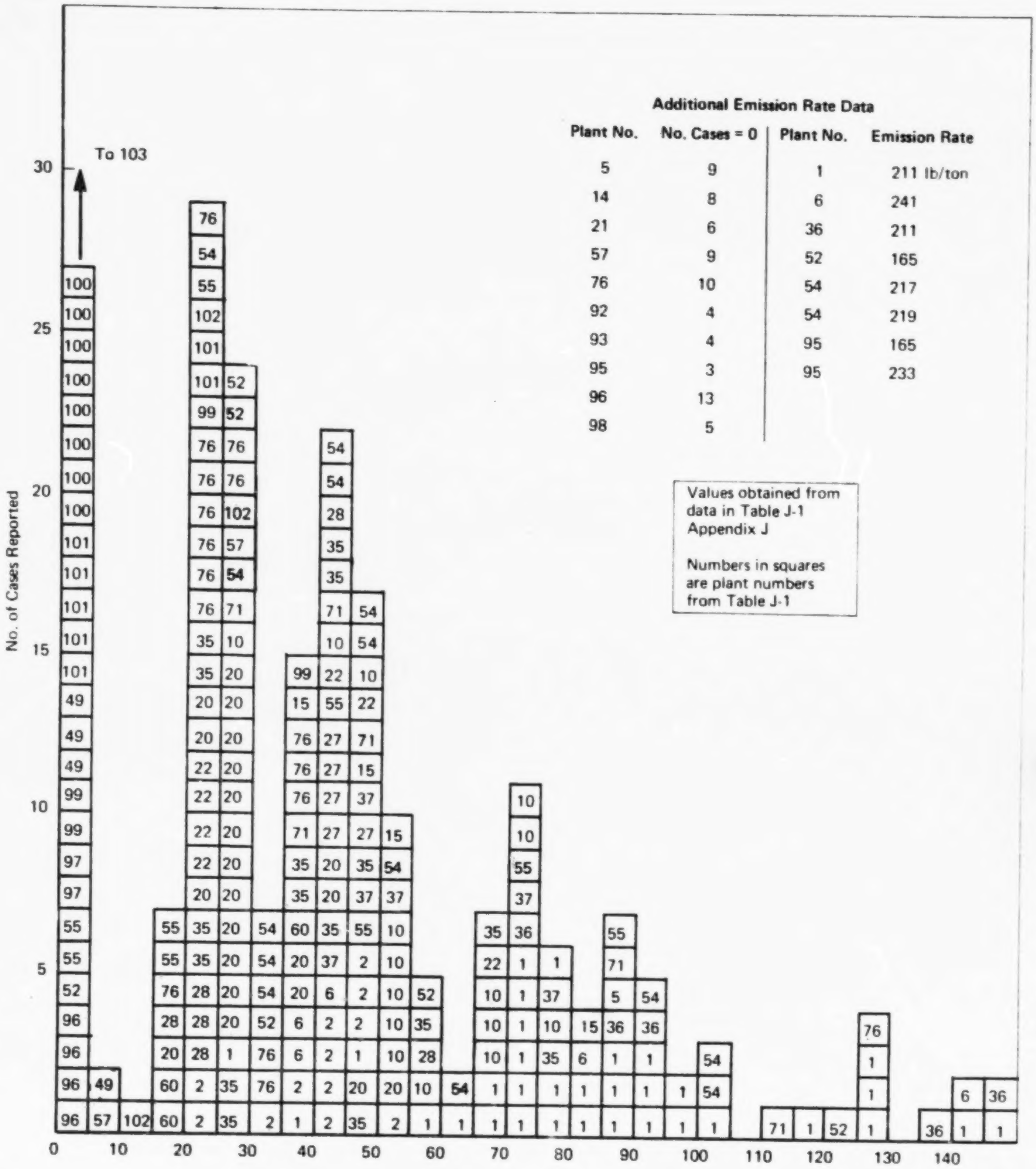
The PHS tests[14] on an experimental incinerator support the above conclusions. The concentration of carbon monoxide was found to be below the limits of their detector sensitivity (30 ppm) excepting for short periods after a charge when the surge in pyrolysis gas evaluation depleted the available oxygen. Additional evidence of the importance of overbed mixing is provided by the Bureau of Mines data on incineration[26] and the work of Mayers[27] on coal stokers.

The compilation of emission data and emission rates in Table J-1 (Appendix J) and Figure V-8 do not show any clear dependence on either excess air or furnace type. The lack of a clear relationship of CO emission to furnace type, however, appears to result, in part, from the small number of data points for any one furnace type and the relatively large variation found in CO emission rates within any single type.

Carbon monoxide emission rates (lbs/ton of refuse) were calculated using a carbon balance and assuming that most of the carbon in refuse appears as either carbon monoxide or carbon dioxide in the flue gases. The emission rates are calculated by multiplying the mole fraction of carbon in the flue gas appearing as carbon monoxide (%CO/[%CO+%CO$_2$]) by the weight of carbon monoxide equivalent to the carbon in one ton of refuse; using the standard refuse composition shown in Appendix C and Table IV-10.

The average furnace emission factor for 302 data points, collected on 33 incinerators, is 38.6 lbs/ton of refuse; with a standard deviation of 44.7 lbs/ton. However, if the data are grouped to produce an average value for each plant, and the resulting set of 33 consolidated values is averaged, the resulting average furnace emission factor is 33.2 lbs/ton of refuse, with a standard deviation of 34.1 lbs/ton. The large standard deviation suggests the wide variability in measured CO emission rates between plants.

The validity of the value 33.2 lbs/ton as a representative national average emission factor is still in doubt, however, due to the anticipated effect of furnace design (especially the flue gas mixing patterns and operating practices) on emission rate. Since it is felt that such a dependence exists, 33.2 lbs/ton does not truly represent a properly weighted average value. One can, however, apply the appropriate mixing effectiveness factors (Table V-7) to the data for 29 of the 33 plants where the grate/furnace type is known to reduce the 32.2 lbs/ton value to that corresponding to an MEF value of unity. These calculations result in a furnace emission factor of 29.44 lbs/ton of refuse (MEF=1). This value, multiplied by the MEF for different grate/furnace types, yields the desired carbon monoxide furnace emission factors. A summary of these factors may be found in Subsection I (Furnace Emission Factor Summary) below.



**Additional Emission Rate Data**

| Plant No. | No. Cases = 0 | Plant No. | Emission Rate |
|---|---|---|---|
| 5 | 9 | 1 | 211 lb/ton |
| 14 | 8 | 6 | 241 |
| 21 | 6 | 36 | 211 |
| 57 | 9 | 52 | 165 |
| 76 | 10 | 54 | 217 |
| 92 | 4 | 54 | 219 |
| 93 | 4 | 95 | 165 |
| 95 | 3 | 95 | 233 |
| 96 | 13 | | |
| 98 | 5 | | |

Values obtained from data in Table J-1 Appendix J

Numbers in squares are plant numbers from Table J-1

FIGURE V–8 HISTOGRAM OF CALCULATED CARBON MONOXIDE EMISSION RATES (Pounds per Ton of Refuse)

## D. HYDROCARBON EMISSION

The hydrocarbon emission from municipal incinerators does not constitute a large fraction of the total emitted pollutant weight. These pollutants are important, however, as a result of the role of hydrocarbons in photochemical smog formation and because many of the hydrocarbon species are odorous. Although many different definitions of hydrocarbons are used in the air pollution literature, this discussion will consider "hydrocarbon" to include all carbon-hydrogen containing compounds, except polynuclear hydrocarbons (which are discussed in Part E of this section), which exist in the gas or low-viscosity liquid phase in the incinerator environment. Heavy tars which appear as particulate are included as combustible particulate. This broad definition encompasses aldehydes, ketones, paraffinic and unsaturated hydrocarbons, organic acids, alcohols, ethers, etc.

As discussed above and in Appendix H (The Incineration Process), hydrocarbons arise within the refuse bed by the pyrolysis and cracking of volatile refuse components. Hydrocarbons are destroyed by combustion within the bed and in the overfire volume. It is felt that most of the hydrocarbon emission takes place in the first third of the grate (or first minutes after charging for batch-feed units), when the ignition and initial drying/burning processes are occurring. Under these conditions, the rapid release of combustible makes great demands upon the available air supply and unburned hydrocarbon material passes from the bed into the overfire volume. In the overfire volume, mixing limitations often prevent complete combustion before these materials pass to the stack.

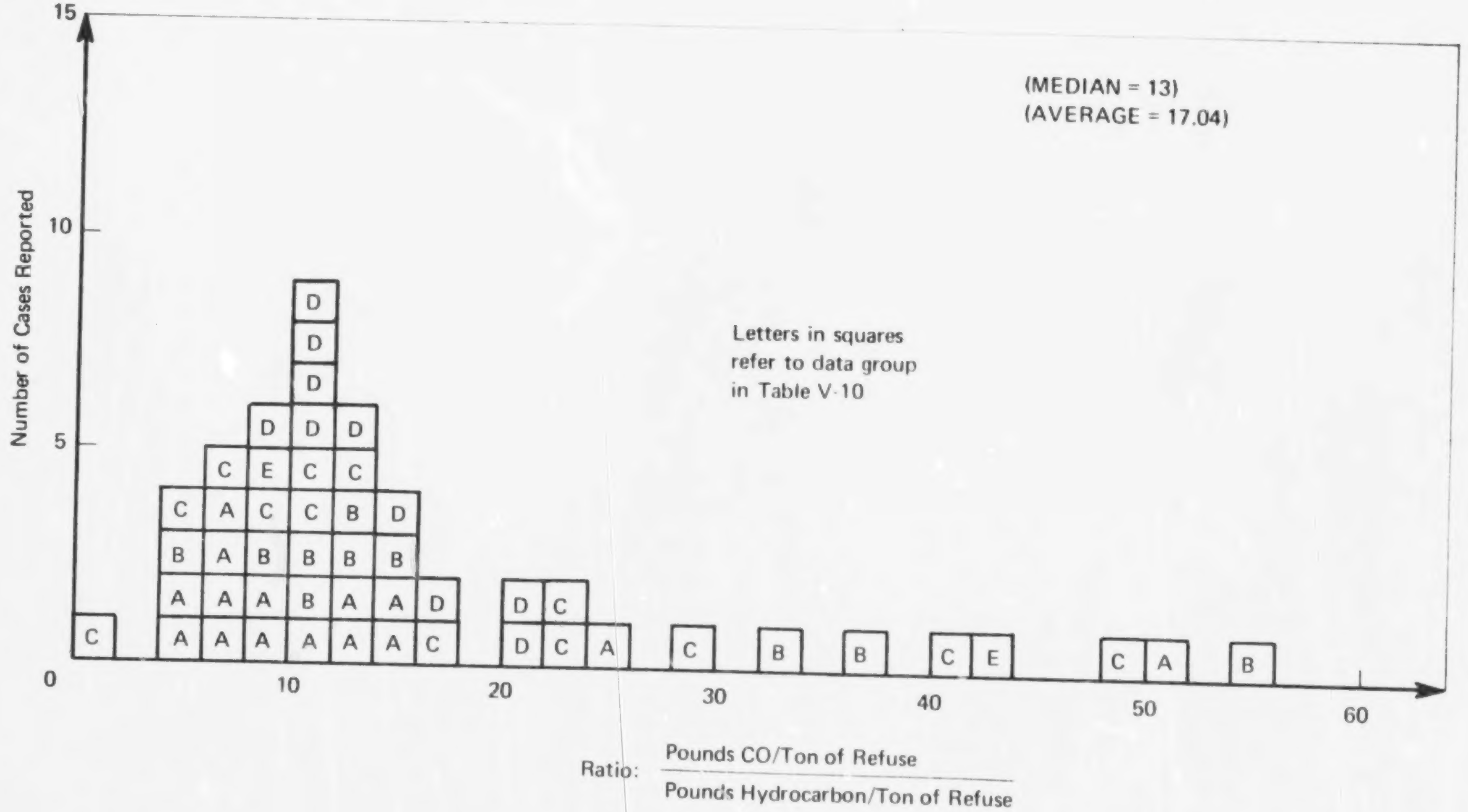
The combustion of hydrocarbons has been shown by many investigators[31] to consist of two stages: rapid oxidation to carbon monoxide (CO) followed by slow oxidation of the CO to carbon dioxide. As a result, hydrocarbon emissions appear always to be associated with emission of carbon monoxide. Also, because of the faster rate of the hydrocarbon to CO reaction, hydrocarbons "succeed" better in competition for the available oxygen such that the ratio of CO to hydrocarbon is always greater than unity.

Because of the limited hydrocarbon emission data, it was felt that correlation of hydrocarbon and CO emission should be explored. Hydrocarbon and CO paired data were found for reported PHS tests[14,15,16] made on a 3-TPD pilot incinerator, and in one full-scale test. These data are reported in Table V-10 and the CO/hydrocarbon ratio presented as a histogram in Figure V-9. From these data, a median CO:hydrocarbon ratio of 13:1 was identified. When this value is combined with the CO furnace emission factor developed above (29.44 lbs/ton) a hydrocarbon furnace emission factor of 2.26 lbs/ton of refuse (MEF=1) is obtained. As in the case of other combustible pollutants, this value should be multiplied by the appropriate mixing effectiveness factor to yield furnace emission factors appropriate to a specific grate/furnace system.

## TABLE V-10

## SUMMARY OF DATA RELATING HYDROCARBON AND CARBON MONOXIDE EMISSIONS[14,15,16]

| | Carbon Monoxide (CO) lb/ton | Hydrocarbons (HC) lb/ton | CO/HC Ratio |
|---|---|---|---|
| A. Fuel – 50% Moisture[15] (PHS 3-TPD Test Unit) | 10.3 | 1.9 | 5.42 |
| | 12.6 | 1.9 | 6.63 |
| | 17.4 | 2.5 | 6.96 |
| | 10.3 | 0.78 | 13.20 |
| | 16.2 | 1.8 | 9.00 |
| | 11.0 | 1.4 | 7.85 |
| | 16.8 | 1.2 | 14.00 |
| | 7.5 | 1.4 | 5.35 |
| | 56.0 | 1.1 | 50.90 |
| | 22.7 | 1.7 | 13.35 |
| | 29.7 | 3.9 | 7.61 |
| | 30.2 | 1.2 | 25.16 |
| | 31.3 | 3.2 | 9.78 |
| | 27.9 | 1.8 | 15.50 |
| | 13.4 | 1.3 | 10.30 |
| B. Fuel – 25% Moisture[15] (PHS 3 TPD Test Unit) | 33.4 | 2.6 | 12.84 |
| | 22.3 | 2.0 | 11.15 |
| | 14.1 | 1.6 | 8.81 |
| | 20.4 | 1.7 | 12.00 |
| | 20.7 | 1.4 | 14.78 |
| | 15.1 | 2.2 | 6.86 |
| | 9.9 | 0.9 | 11.00 |
| | 28.2 | 0.76 | 37.10 |
| | 18.0 | 0.55 | 32.72 |
| | 40.0 | 0.72 | 55.55 |
| C. Fuel – High Volatile[16] (PHS 3 TPD Test Unit) | 65.2 | 3.8 | 17.15 |
| | 143.5 | 6.5 | 22.07 |
| | 7.7 | 0.7 | 11.00 |
| | 8.9 | 0.4 | 22.25 |
| | 17.1 | 1.3 | 13.15 |
| | 27.0 | 3.4 | 7.94 |
| | 14.6 | 0.3 | 48.66 |
| | 12.1 | 0.3 | 40.33 |
| | 0.7 | 0.6 | 1.16 |
| | 53.5 | 4.9 | 10.91 |
| | 41.5 | 1.4 | 29.64 |
| | 11.8 | 0.4 | 29.50 |
| | 5.6 | 0.7 | 8.00 |
| | 7.7 | 1.9 | 4.05 |
| D. Fuel – Prepared Refuse[14] (PHS 3 TPD Test Unit) | 12.0 | 0.72 | 16.66 |
| | 9.8 | 0.78 | 12.56 |
| | 28.0 | 2.1 | 13.33 |
| | 18.0 | 0.82 | 21.95 |
| | 26.0 | 2.5 | 10.40 |
| | 4.8 | 0.5 | 9.60 |
| | 6.1 | 0.47 | 12.97 |
| | 24.0 | 1.4 | 17.14 |
| | 7.7 | 0.37 | 20.81 |
| | 8.0 | 0.64 | 12.50 |
| E. Fuel – Municipal Refuse (Plant No. 57, Table J-1, Appendix J) | 19.48 | 0.46 | 42.34 |
| | 19.72 | 2.14 | 9.21 |
| Average of 51 Points | 22.27 | 1.58 | 17.04 |
| Standard Deviation | 21.86 | 1.23 | 12.63 |



(MEDIAN = 13)
(AVERAGE = 17.04)

Letters in squares refer to data group in Table V-10

FIGURE V–9 HISTOGRAM OF RATIO OF EMISSION FACTORS FOR CARBON MONOXIDE AND HYDROCARBONS[14,15,16]

Table V-11 summarizes the limited data on hydrocarbon emission for full-scale incinerator units. From these data, the average emission factor for hydrocarbons is 1.84 lbs/ton; in good agreement with the value developed by ratio to carbon monoxide. The large standard deviation seen for these data illustrates the probable variability of this emission factor. It can also be noted from Table V-11 that the ratio of hydrocarbons to formaldehyde is high, almost 10 to 1. This would be expected, since, as in the case of hydrocarbon-to-CO combustion, the formaldehyde oxidation rate is faster than that for more complex hydrocarbons.

The recommended furnace emission factors for hydrocarbons, modified by application of the mixing effectiveness factor, are presented in Subsection I (Furnace Emission Factor Summary) below.

## TABLE V-11

### EMISSION RATES OF SPECIFIC ORGANIC SPECIES
(lbs/ton of refuse)

| Plant No.* | Hydrocarbons as $CH_4$ | Organic Acids as Acetic Acid | Aldehydes as Formaldehyde | Notes |
|---|---|---|---|---|
| 57 | 0.27 | 0.16 | 0.02 | |
| | 0.46 | 0.11 | 0.30 | See also Table V-9 |
| | 2.41 | $<$0.14 | 0.16 | See also Table V-9 |
| 14 | 0.09 | $<$0.08 | 0.024 | |
| | 0.2 | $<$0.08 | 0.09 | |
| 70 | 6.3 | 0.1 | 0.03 | |
| | 3.94 | 0.1 | 0.001 | |
| 103 | 2.6 | 0.06 | 0.28 | |
| | 0.32 | 0.06 | 0.24 | |
| 5 | | | 0.075 | Start-up |
| | | | 0.058 | |
| | | | 0.263 | |
| | | | 0.188 | |
| | | | 0.397 | Burning Garbage |
| | | | 0.015 | Start-up |
| | | | 0.041 | |
| | | | 0.840 | |
| | | | 0.612 | Burning Garbage |
| Average | 1.84 | 0.099 | 0.190 | |
| Standard Deviation | 2.16 | 0.033 | 0.231 | |

* Table J-1, Appendix J

## E. POLYNUCLEAR HYDROCARBON EMISSION

The emission of polynuclear hydrocarbons constitutes a minute fraction of the total emissions from municipal incinerators. Several of these compounds have been identified, however, as carcinogenic agents and therefore are treated separately. It is expected that the factors that favor high emission rates of carbon monoxide and low molecular weight hydrocarbons will also favor high emission rates for polynuclear hydrocarbons (PNH). The emission factors for PNH are based on the PHS tests,[36] the only available data source. The emission of PNH from the five units tested by PHS with the corresponding CO emission rates are presented in Table V-12. The compositions of the PNH for these tests are given in Table V-13.

TABLE V-12

FURNACE EMISSION RATES FOR POLYNUCLEAR HYDROCARBONS[36]

| No. | Type of Unit | Polynuclear Hydrocarbons (grams per ton refuse) | Carbon Monoxide (lbs per ton refuse) | (lb CO/lb PNH) |
|---|---|---|---|---|
| 1 | 250-ton/day Municipal (before settling chamber) | 0.035 | 0.67 | 8,670 |
| 2 | 50-ton/day Municipal (before scrubber) | 0.284 | 4 | 6,400 |
| 3 | 50-ton/day Municipal (after scrubber) | 0.015 | <2. | <60,520 |
| 4 | 5.3-ton/day Commercial Single Chamber | 1.92 | 4.3 | 1,000 |
| 5 | 3-ton/day Commercial Multiple Chamber | 1.94 | 25. | 5,810 |

–Average of Multiple Chamber (No. 1, 2 and 5) furnace emission ratio: 6,960 lb CO/lb PNH

–Standard Deviation: 1,510 lb CO/lb PNH

–Average PNH emission factor: $4.2 \times 10^{-3}$ lb/ton of refuse at unit Mixing Effectiveness Factor

The data show two significant effects. First, as could be expected based on analogy with other combustible pollutants, the emission rates are highest for small units, and generally are high when the carbon monoxide (CO) emission is high. It can also be seen that the ratio of CO to PNH does not vary greatly between the multiple-chamber results. Second, the sprays for the 50-TPD unit decreased the polynuclear content by 95%, while reducing the particulate content by 68%. This very large reduction suggests that the PNH may be preferentially absorbed on the large particles, but the data are not sufficiently comprehensive to support this speculation.

## TABLE V-13

## COMPOSITION OF POLYNUCLEAR HYDROCARBON OF PARTICULATE MATTER EMITTED[36]

| | Micrograms/Gram of Particulate | | | | | | | | | | | Particulate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | Benzo (a) - pyrene | Pyrene | Benzo (e)-pyrene | Perylene | Benzo (ghi) perylene | Anthacene | Coronene | Anthra-cene | Phenan-threne | Fluoran-thene | Benz (a) Anthracene | $\frac{\text{Lbs}}{\text{Ton}}$ |
| 1 | 0.016 | 1.9 | 0.08 | – | – | – | 0.06 | – | – | 2.2 | 0.09 | 18 |
| 2 | 3.3 | 28 | 6.5 | – | 19 | – | 8.2 | – | 9.8 | 2.5 | – | 8.1 |
| 3 | 0.15 | 3.6 | 0.97 | – | 1.1 | – | 1.1 | – | – | 5.5 | 0.26 | 2.6 |
| 4 | 58 | 350 | 49 | 3.3 | 98 | 7.1 | 23 | 51 | 150 | 240 | 5.0 | 4.1 |
| 5 | 180 | 2600 | 180 | 36 | 540 | 45 | 130 | 53 | 62 | 2400 | 240 | 6.6 |

In order to obtain emission factors for different furnace types from the very limited data, it was decided to use the ratio of CO to PNH as the correlating parameter. Because of the sensitivity to the volatile carbon content of refuse, it also seems appropriate to suggest the effects of changing refuse composition for projections into the future. The value presented is very uncertain and underlies the need for more extensive data on these furnace emission factors. In estimating the efficiency of the APC devices in reducing PNH emission, one third of the hydrocarbon is assumed to be in the gas phase and two thirds in the particulate. Thus, dry collectors (such as electrostatic precipitators) could effect a maximum PNH reduction of 66%.

It should be noted that the PNH furnace emission factor resulting from this analysis ($4.2 \times 10^{-3}$ lbs/ton of refuse; MEF=1) is 350 times larger than the measured value reported by PHS of $1.17 \times 10^{-5}$ lbs PNH/ton.[36] This difference reflects the use of the carbon monoxide emission factor developed above (29.44 lbs/ton; MEF=1) in contrast to the 0.67 lb/ton CO emission factor measured in the 250-TPD unit tests. In effect, this result suggests that the particular units studied by PHS were better designed (or better operated during the testing period) than most conventional plants. As a result, the combustible pollutants, including CO and PNH, were well burned out. The high PNH emission factor suggested in this report is supported by a thin data base and is subjected to an almost 60-fold leverage by the CO emission factor correlation. It is clear, therefore, that additional data are needed to confirm these assumptions.

The recommended PNH furnace emission factors, modified by application of the mixing effectiveness factors, are presented in Subsection I (Furnace Emission Factor Summary) below.

## F. NITROGEN OXIDE EMISSION

The emission of nitrogen oxides ($NO_X$) from the incineration of municipal solid waste is usually small in comparison to that emitted by other sources, particularly the internal combustion engine. They merit consideration, however, as a consequence of their important role in photochemical smog formation. Nitrogen oxides (primarily NO and $NO_2$) are formed at elevated temperatures within the incinerator furnace by the reaction of nitrogen and oxygen, always present in the combustion air. From equilibrium considerations, one would not expect to find $NO_X$ compounds in the effluent gases as, at ambient temperatures, dissociation to the elements is favored. Their rate of formation within the combustion zone and their rate of dissociation as the temperature falls, however, is governed by relatively slow kinetic mechanisms, such that $NO_X$ compounds formed in the flame region are "frozen." Considerations of the processes whereby these pollutants are formed within an incinerator thus requires consideration of the kinetics of $NO_X$ reactions.

Consideration of the equilibrium constant for nitric oxide formation from the elements

$$[NO]^2/[N_2][O_2] = 21.21 \exp(-43,260/RT) \qquad (10)$$

whereas T is in °K, and the terms in brackets are the partial pressures of the noted species, indicates that the equilibrium concentration of nitric oxide varies from 7 ppm for combustion of refuse with 300% excess air and an adiabatic flame temperature of 1100°F, where dilution cooling overcomes the effect of an increase in oxygen concentration, to 440 ppm for combustion with 100% excess air, and an adiabatic flame temperature of 2000°F. These equilibrium values bracket the concentrations encountered in practice (reported by Rehm[32] to range from 9 to 220 ppm). There is substantial evidence that the nitric oxide content of the stack gases is limited by the rate of formation of nitric oxide and not by equilibrium considerations.

The rate of formation of nitric oxide at high temperatures, in air-rich mixtures, is given by a kinetic expression developed by Zeldovich,[33]

$$\frac{d\ f_{NO}}{dt} = 3 \times 10^4\ f_{N_2}\ f_{O_2}^{1/2}\ [P/RT]^{1/2} \exp\left[\frac{-133,800}{RT}\right] \qquad (11)$$

where f designates the mole fraction of the species denoted by the subscript, t is time in seconds and T is in °K. The pre-exponential constant and the activation energy were adjusted to take into account data[34] obtained after publication of the Zeldovich article. The use of the above expression predicts concentration of nitric oxide less than one part per million for any reasonable residence time at 2000°F. Temperatures in excess of 3000°F are required to produce the concentrations of nitric oxide actually observed in incinerators. From these considerations, it appears that the nitric oxide is probably formed in the high temperature flame zones. Since the temperatures within the burning refuse bed are usually below 2400°F and the gas volume within the bed is oxygen-deficient, it is tentatively concluded that the nitric oxide is formed at the flame front of the refuse pyrolysis products above the bed. Any variables that will increase the temperature or the oxygen concentration in the flame zones is expected to increase the nitric oxide formation. These qualitative conclusions are in general agreement with the limited data on nitric oxide emission. The nitric oxide formed at the high temperatures is subsequently partially oxidized to $NO_2$. No distinction between the two oxides will be made here.

The available data on $NO_X$ has been compiled and is reported in Appendix J (Table J-2). These data fall into two groups: the PHS data[14,15,16,28] which is referenced to the test series, and municipal scale incinerator data listed by plant number. Because the nitric oxide emissions are determined by flame temperature, it has been observed[16,35] for a variety of fuels that the heating value of the fuel provides a better correlating parameter than the mass of fuel. The data from Table J-2, therefore, have been converted to units of pounds of $NO_X$ (expressed as $NO_2$) per million Btu and used to generate the histogram of $NO_X$ emission rates in Figure V-10. The median emission rate for the small-scale PHS tests is one pound of $NO_X$ per $5.9 \times 10^6$ Btu heat release, or 0.17 pound $NO_X$ per $10^6$ Btu's.

Correlations of $NO_X$ formation that have been proposed by PHS for coal, gas and oil[35] are:

$$\text{lb } NO_X/\text{hr} = [(\text{Btu/hr})/6.60 \times 10^6]^{1.18} \quad \text{for gas} \qquad (12)$$

$$\text{lb } NO_X/\text{hr} = [(\text{Btu/hr})/4.44 \times 10^6]^{1.18} \quad \text{for oil} \qquad (13)$$

$$\text{lb } NO_X/\text{hr} = [(\text{Btu/hr})/3.8 \times 10^6]^{1.18} \quad \text{for coal} \qquad (14)$$

If the emission rate of one pound $NO_X$ per $5.9 \times 10^6$ Btu associated with the 3 TPD PHS test incinerator ($1.11 \times 10^6$ Btu per hour with 4,450 Btu per pound refuse) and the corresponding $NO_X$ emission rate (0.1885 pound per hour) are cast into the same functional form as Equations (11), (12), and (13), the resulting constant term within the brackets is $4.6 \times 10^6$. However, it must be recognized that this correlation provides only rough estimates since factors such as furnace heat loss and excess air which are known to influence $NO_X$ production are not taken into account. That the data for the three fossil fuels are correlated best with an exponent on firing rate greater than unity is a consequence of the increase in the mean emission factor with increases in furnace size.

The PHS[35] obtained a comparable correlation for refuse combustion in small units with an exponent of 1.14 in place of 1.18. In the absence of sufficient data to obtain a reliable estimate of the exponent for municipal-scale incinerators, it was decided to use the value of 1.18 in extrapolating data from one size to another. The PHS 3-ton experimental incinerator data was used to obtain the constant for refuse. Substitution of the emission factor of 0.17 pound $NO_X$ per $10^6$ Btu gives the following relationships:

$$\text{lb } NO_X/10^6 \text{ Btu} = 0.17 \left[\frac{C}{3}\right]^{0.18} \qquad (15)$$

$$\text{lb } NO_X/\text{ton of refuse} = 3.4 \times 10^{-4} \left[\frac{C}{3}\right]^{0.18} (\text{refuse heating value} - \text{Btu/lb}) \qquad (16)$$

where C is the furnace capacity in tons per 24-hour day.

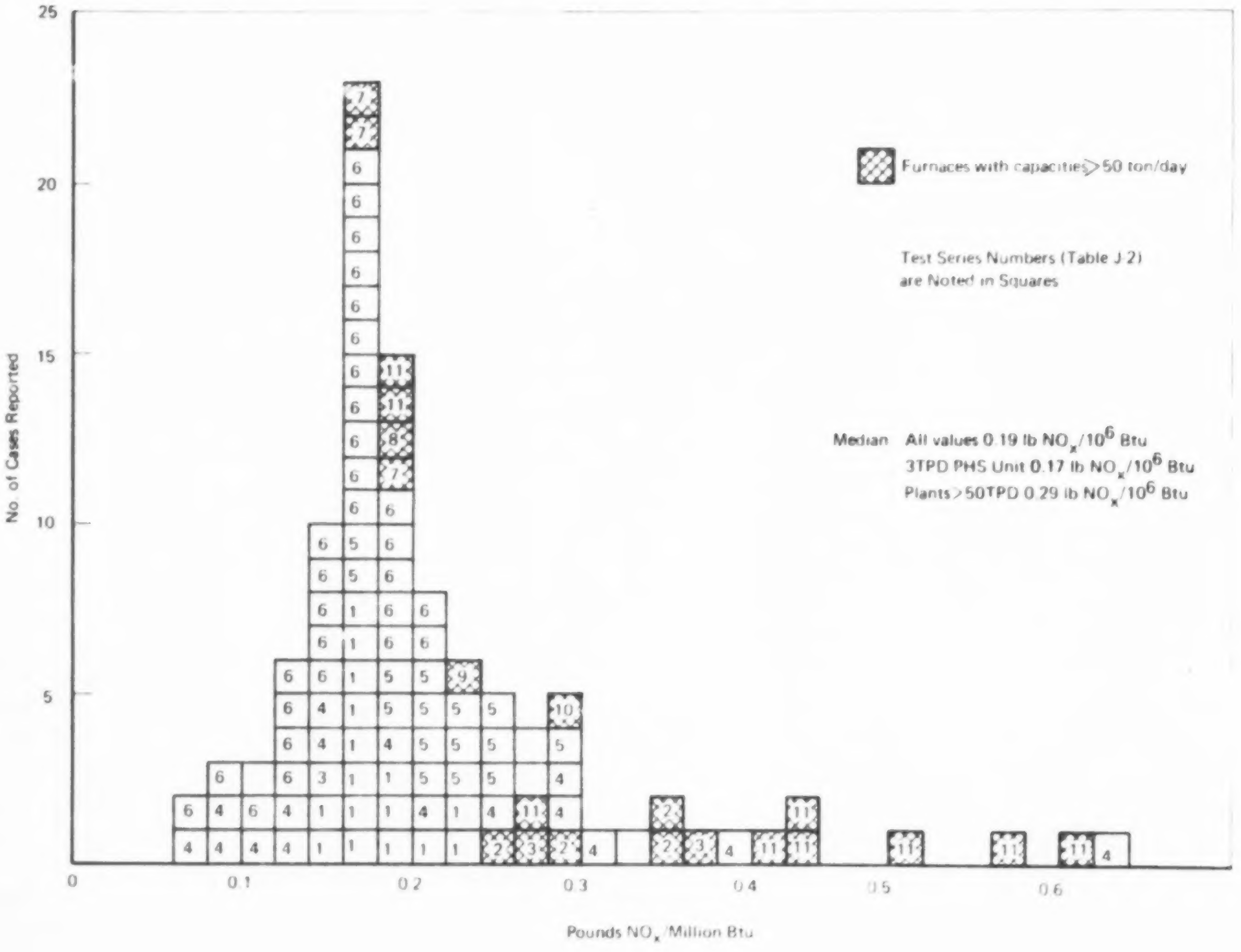


FIGURE V–10 EMISSION RATE: POUNDS $NO_x$ (AS $NO_2$) PER MILLION BTU

Although this relation is very useful, it does not recognize the effect of three variables that are known to affect $NO_x$ emission. First, increases in excess air will result in increases in $NO_x$ emission[14, 15] up to excess air levels of about 300% beyond which further increases in excess air cause the flame temperature and NO formation rate to be reduced. Second, increases in underfire air rate will reduce the $NO_x$ emission[35] since these result in smaller fractions of the combustion occurring in the flame above the bed, the region in which most of the $NO_x$ is formed. The effect of these variables on $NO_x$ emissions for municipal-scale systems, however, cannot yet be quantified. The third variable known to affect $NO_x$ emission is the nitrogen content of the fuel. Experiments by Shaw and Thomas[41] have shown significant amounts of $NO_x$ are formed in premixed flames of nitrogen-containing hydrocarbons (butylamine, pyridine and methyl cyanide) at temperatures as low as 1650°F. These results are not duplicated in diffusion flames. It is still a matter of speculation, therefore, as to whether the nitrogen content of refuse should be considered in estimating $NO_x$ emission rates for incinerators where it has been suggested that $NO_x$ is formed in the diffusion flame of the refuse pyrolysis products.

Equation (15) provides a correlation to calculate $NO_x$ emission factors for incinerators of any specified capacity. In order to obtain emission factors suitable for use in estimating national $NO_x$ emission levels, it is necessary to define average plant capacity values for the various grate/furnace systems. The assumed plant capacities and resulting emission factors are presented in Subsection I (Furnace Emission Factor Summary) below.

## G. SULFUR OXIDES AND HYDROGEN CHLORIDE EMISSIONS

### 1. Sulfur Oxides

The importance of sulfur oxides as air pollutants is well-recognized. The potential contribution to sulfur oxide pollution from refuse incineration, however, is small enough to suggest the use of refuse as a partial replacement for high sulfur fossil fuels to reduce the total sulfur dioxide emissions. Therefore, it is of value to examine the sulfur oxide pollution potential of municipal incineration to quantify, if possible, the extent to which the incinerators contribute to national sulfur oxide air pollution.

#### a. Sulfur in Refuse

In Chapter IV, data were analyzed to determine an average refuse composition and, from published data, the chemical composition of the major components comprising refuse was evaluated (Appendix C and Table IV-11). The resulting sulfur content of the average refuse was shown to be 0.0985%. This sulfur is primarily associated with paper, food wastes, and yard wastes. For the sulfur compounds found in these refuse components, incineration will result in the formation of sulfur dioxide. The sulfur content of rubber, although relatively high, adds little to the total *average* sulfur oxide emission from incinerators because of the low concentration of rubber in refuse. Over short periods of time, however, as when several automobile tires are being burned, high instantaneous sulfur oxide emissions may be observed.

Substantial amounts of other sulfur-containing compounds such as demolition plaster waste, wallboard, and other inorganic sulfates may also be charged to an incinerator. It is not felt, however, that much of the sulfate will be reduced in the furnace and thus contribute to the sulfur oxide emission. As a result, it is concluded that, based on refuse analysis, the total sulfur oxide furnace emission rate (corresponding to 0.0985% sulfur) will be 3.94 lbs/ton of refuse (expressed as sulfur dioxide).

b. Emission Data

The data in Table V-14 can be compared with the sulfur oxide emission rates calculated on the basis of average refuse composition. It should be noted that little $SO_2$ absorption is expected in APC systems (see Section VIIB) such that stack $SO_2$ emission rates are approximately the same as furnace emission rates. On this basis, the data of columns 3 and 5 were combined to yield an average emission rate of 2.32 lb $SO_2$/ton of refuse with a standard deviation of 1.76 lbs/ton. This is in rough agreement with the value calculated from refuse composition and corresponds to a refuse sulfur content of .06%. The large standard deviation suggests the wide variation to be expected in $SO_2$ measurements.

The data on sulfuric acid emissions ($SO_3$) are anomalous for two reasons: First, the refuse sulfur content corresponding to the reported $SO_3$ levels (and particularly if the $SO_2$ flow is also considered) is 2 to 3 times greater than is predicted from any of the several compositions which have been suggested for typical solid wastes. Second, we have not conceived of any reasonable mechanism for the formation of $SO_3$ directly from ordinary refuse materials, or from oxidation of sulfur dioxide.

The data on sulfuric acid emissions ($SO_3$) suggest unreasonably high sulfur concentrations in refuse. The average value for total sulfur oxide stack emissions of 11.01 lbs/ton of refuse (expressed as $SO_2$) corresponds to a refuse sulfur content of 0.28%. This is much higher than is reported in the literature for any typical refuse analysis. The data from Plants No. 57, 14, and 103 on sulfuric acid emissions, however, are somewhat in doubt. The investigator for these tests has reported that $SO_2$ absorption occurred in the alkali solution in the collection train (which can subsequently oxidize to sulfate); interference by organic acids in the sulfate test, and the carry-over of particulate matter into his absorption vessel

## TABLE V-14

## EMISSION RATES OF SULFUR COMPOUNDS IN INCINERATOR FLUE GASES

| (1) Plant No.* | (2) APC System | (3) Furnace Emissions lb $SO_2$ Per Ton of Refuse | (4) Furnace Emissions lb $H_2SO_4$ Per Ton of Refuse | (5) Stack Emissions lb $SO_2$ Per Ton of Refuse | (6) Stack Emissions lb $H_2SO_4$ Per Ton of Refuse | (7) Total Stack Emissions (as $SO_2$) lb Per Ton of Refuse |
|---|---|---|---|---|---|---|
| 20 | Wet Baffle | 0.70 | | 0.66 | Not Meas. | |
| 20 | | 1.54 | | 1.85 | Not Meas. | |
| 20 | | 0.48 | | 0.55 | Not Meas. | |
| 57** | Water Sprays, Cyclones | | | 1.17 | 4.19 | 5.36 |
| 57** | | | | 2.82 | 5.60 | 8.42 |
| 57** | | | | 3.58 | 6.74 | 10.32 |
| 14** | Wet Bottom Expansion Chamber | | | 2.10 | 5.30 | 7.40 |
| 14** | | | | 2.04 | 10.24 | 12.2 |
| 103** | None | | | 3.5 | 12.0 | 15.5 |
| 103** | | | | 5.90 | 15.07 | 20 97 |
| 103** | | | | 1.3 | 3.9 | 5.20 |
| 103** | | | | 6.00 | 7.76 | 13.76 |
| 45 | Pilot Bag Filter | 1.13 | 2.04 | Not Meas. | .03*** | |
| | | | | | 1.70 | |
| — | Unknown | | | 4.15 | Not Meas. | |
| Average (lbs/ton) | | 0.96 | N/A | 2.74 | 6.74 | 11.01 |
| Standard Deviation (lbs/ton) | | 0.47 | N/A | 1.80 | 4.24 | 5.17 |

* See Table J-1, Appendix J.

** Author noted possibility of $SO_2$ absorption and subsequent sulfite oxidation in absorbent solution in the collecting train, interference by organic acids and particulate carry-over (giving a high reading) in $H_2SO_4$ determination.

*** Not included in average.

(which interferes with the subsequent gravimetric $SO_4 =$ determination). All three of these effects would tend to increase the reported $SO_3$ concentration. The data for Plant No. 45, for example, show significantly lower $SO_3$ values. We concluded, therefore, that these data are of doubtful worth.

The kinetics of the homogeneous gas phase oxidation of $SO_2$ to $SO_3$ has been studied only to a limited extent. In the absence of either a solid or gaseous catalyst, the reaction proceeds extremely slowly[37] up to temperatures exceeding 1500°F, although equilibrium favors $SO_3$ formation. At temperatures in excess of 1800°F, equilibrium data predict a very low equilibrium $SO_3$ concentration, even if the rate of reaction is sufficiently fast to achieve equilibrium conversion.

The major source of $SO_3$ in combustion processes where no catalytic solid surfaces are available is believed to be the homogeneous gas phase reaction of $SO_2$ with atomic oxygen.[1] The formation, and hence availability, of these oxygen atoms varies with the combustion kinetics and the type of fuel being burned. While such detailed data are not available on refuse combustion, it would not be expected that the gas phase oxidation of $SO_2$ to $SO_3$ would be appreciable via this mechanism, as it results in only a minor conversion of $SO_2$ (approximately 1%) in the combustion of other fuels.

Reaction of $SO_2$ to $SO_3$ via the catalytic action of surfaces present in the combustion or high temperature zone in furnaces has not been demonstrated to contribute appreciably to $SO_2$ oxidation. Ash, iron oxide, or vanadium pentoxide-coated superheater elements in boilers do not appreciably influence the $SO_3$ content of gases flowing through boilers. The $SO_2$ injected into fossil fuel boilers for emission control either do not result in oxidation of $SO_2$ or react with the $SO_3$ reaction product, as little $SO_3$ appears in the effluent gases. Consequently, a large conversion of $SO_2$ to $SO_3$ via the catalysis action of ash and other solids is not anticipated in incinerators.

The presence of nitrogen oxides in the flue gas also influences the mechanism and overall kinetics of oxidation of $SO_2$. Since $NO_X$ is also present in the fossil fuel-fired boiler gases, and does not result in appreciable $SO_2$ oxidation, the same lack of effectiveness would be expected at the comparable $NO_X$ concentrations in incinerator flue gases.

Based on these considerations, it is unlikely that significant conversion of $SO_2$ to $SO_3$ occurs in incinerator systems.

Although few definitive experiments have been performed differentiating between sulfur dioxide and sulfur trioxide in incinerator flue gases, some emission data have been reported which suggest that a substantial fraction of the sulfur oxide content of the flue gases is $SO_3$ (Table V-13). Based on the arguments above, it is unlikely that the $SO_3$ arose from oxidation of sulfur dioxide. Two possibilities are suggested:

- Sulfate is decomposed in the furnace to $SO_3$ and an oxide; or
- Sampling and analytical errors indicate $SO_3$ when, indeed, little is present.

The first mechanism is unlikely. Brief review of equilibrium data suggests thermal stability of most sulfates at temperatures near 3000°F. Reduction of sulfates by the abundant carbon and CO present is possible at these temperatures; however, sulfur dioxide results from this reaction.

Sampling and analytical errors are quite plausible explanations for at least part of the indicated presence of $SO_3$ and $H_2SO_4$ in incinerator flue gases. Sulfate can be introduced into the alkali scrubbing liquor in the collection train or as fine particulate which passes through coarse or imperfect filtration media. Also, sulfite ion (formed in alkali by $SO_2$ absorption) is readily oxidized to sulfate by oxygen contained in the flue gases. In this regard, it is of interest to note that essentially no calcium sulfite has been found in the effluent sludge from the lime-water scrubbers used for $SO_2$ removal from flue gases. Calcium sulfate is the observed product.

Based on this reasoning and the limited and uncertain data to the contrary, therefore, it will be assumed that sulfur in refuse is largely (>95%) released as $SO_2$ and remains as $SO_2$.

It has been suggested by Kaiser[38] that up to three-fourths of the sulfur present in refuse is absorbed by alkali oxides and is fixed as a solid in the residue and fly ash. Kaiser's development is based on several sets of paired refuse and residue data, and very limited gas analysis data. In general, the solid phase material balance supports his argument if values of refuse and residue sulfur content, at concentrations of fractions of one percent, could be measured accurately enough and were stable enough over the test period. In one set of data, for example, the refuse concentration "must have been in excess of 0.2% as the . . . (overflow water from the residue conveyor) gained the equivalent amount of sulfur in sulfate form." The uncertainty suggested by such data does not discount Kaiser's hypothesis, but, indeed, it emphasizes the difficulty in closing material balances on highly unhomogeneous flow systems. Certainly, the notion that alkali oxides can absorb $SO_2$ has been clearly established in tests where lime, limestone or crude soda ash have been injected into boilers to effect $SO_2$ emission reductions. What is questioned, however, is the relative importance of this mechanism.

Based on the mean of the gas analysis data in Table V-13 and the average refuse sulfur content, one could speculate that about one-third of the sulfur is absorbed. At this time, however, we feel the data are inconclusive as to the fraction of sulfur removed. It is felt, however, that somewhat less than Kaiser's estimate of three-fourths removal is probable.

Based on the very limited amount of data and the uncertainties in most of the sulfuric acid measurements, it is suggested that an emission factor of 3.94 lbs/ton (expressed as $SO_2$) is an acceptable estimate of the maximum total sulfur oxide air pollution potential of incinerators, although some data[38] suggest a lower value may be appropriate. The reported concentrations of $SO_3$ in incinerator flue gases are difficult to account for and the limited data base and the expressed uncertainties in analytical technique preclude the confident identification of a sulfur trioxide emission factor.

### 2. Hydrogen Chloride

The emission of hydrogen chloride (HCl) from incinerators is a matter of increasing public concern. In addition, HCl poses a severe threat of corrosion in incinerator concepts based on the use of boilers. The principal source of HCl in the incinerator effluent is as a product of the combustion of halogenated polymers, primarily polyvinyl chloride (PVC) and, to a much lesser extent, polyvinylidene chloride (Saran). These materials appear in refuse as housewares, textiles, packaging, toys, etc. Pure PVC resin burns to quantitatively yield 1180 pounds of HCl per ton of PVC. An estimate may be made, therefore, of the HCl emission factor by determining the PVC content of average refuse.

In Chapter IV, the nature of municipal refuse was analyzed and, in particular, the percentage of plastic (Table IV-9) was determined to be 1.0 to 1.1% of the total refuse weight (for 2% moisture of the plastics). Based on review of a variety of sources of market information and in consideration of the delay times of different PVC articles in being discarded (e.g., wrappings are discarded immediately whereas PVC chairs or pipe will be used for several years before being discarded), values were developed for the present and forecast percent PVC in plastics. Because of the frequent use of plasticizers, fillers and other diluents, this analysis was reduced to the equivalent in pure PVC resin. The results of this analysis are presented in Table V-15.

Table V-15 shows the rapid rise to be expected in the emission of HCl from the incineration of municipal solid waste. Other than through controls on PVC manufacture and/or disposal, these emissions will take place. Two factors, however, may limit the air pollution problem to be expected: absorption of HCl by alkali ash materials within the furnace and absorption of HCl in wet APC systems. The first factor, absorption by solids, presumes mechanisms similar to those postulated by Kaiser[38] for $SO_2$ absorption. Although the extent of this effect is unknown, the results would be favorable to reduced HCl emission. The second factor, absorption in scrubber water, results from the high solubility of HCl in water, even at relatively low pH (see section VIIB). This solubility is undoubtedly now responsible for corrosion problems in existing wet scrubbers using recycled, untreated water. It is anticipated that wet scrubbers of the efficiency required to meet contemporary and future particulate air pollution codes may remove as much as 90% of the HCl. The less efficient wetted baffle devices now in common use, probably remove less than 50% of the HCl.

As a consequence of the very limited and inconclusive data available on HCl emissions, the HCl emission factors calculated from refuse composition data (Table V-15) are suggested for interim use.

TABLE V-15

ANTICIPATED GROWTH PATTERNS OF PVC IN AVERAGE REFUSE AND ASSOCIATED HCl FURNACE EMISSION FACTORS*

| Year | % Plastics in Refuse** | % PVC Resin in Plastics | HCl Emission Factor lb HCl per Ton of Refuse*** |
|---|---|---|---|
| 1968 | 1.1 | 7.8 | 0.99 |
| 1970 | 1.3 | 10.0 | 1.50 |
| 1975 | 1.8 | 10.6 | 2.20 |
| 1980 | 2.7 | 8.7 | 2.71 |
| 1990 | 3.5 | 10.9 | 4.41 |
| 2000 | 4.2 | 11.2 | 5.44 |

* **Source:** ADL Estimates.

** As Discarded Basis – Semi-Seasonal State – as defined in Chapter IV (see Table IV-14).

*** Based on quantitative conversion of the chloride in PVC to HCl.

## H. OTHER SPECIES

### 1. Volatile Metals

Some metals, especially lead, zinc and cadmium, are themselves volatile or have oxides which are volatile at incineration temperatures. Under such conditions, a very small particle would be formed, which, due to difficulties in collection, may present an air pollution problem justifying special note. Although the latter metals may be contained in refuse (on galvanized steel or in castings), no specific ash composition data or reliable refuse component data are available to estimate their importance as effluent species. Lead, however, as it appears in tin can solder, can be identified and calculated as a fraction of the metal content. It is likely that the lead, as the oxide, will appear in incinerator flue gases as a submicron fume and, as a consequence, will escape collection by any but the most efficient (99%+) particulate APC devices. With present refuse compositions, this emission approximates 0.032 lb of lead per ton of refuse. Future declines in tin can usage will cause this value to drop in the future.

### 2. Miscellaneous Pollutants

In recent studies, some incinerator emission data have been collected on a number of pollutants which appear in very small concentrations. These data appear in Table V-16.

## TABLE V-16

## SUMMARY OF STACK EMISSION DATA FOR TRACE POLLUTANTS

**I. Hydrogen Fluoride Emission**

| Plant No.* | Emission Rate | | Plant No.* | Emission Rate | |
|---|---|---|---|---|---|
| | ppm (volume) | lb/ton | | ppm (volume) | lb/ton |
| 57 | 3.00 | 0.20 | 103 | 0.85 | 0.016 |
| | 0.00 | 0.00 | | 0.00 | 0.000 |
| | 0.00 | 0.00 | | 0.00 | 0.000 |
| | 0.00 | 0.00 | ** | 1.40 | 0.014 |
| 14 | 0.90 | 0.03 | | 0.65 | 0.002 |
| | 0.00 | 0.00 | | 0.00 | 0.000 |

**II. Selenium Emission****

| | |
|---|---|
| In 0°C Sampling Train Trap Concentrate | 0.05 ppm (by weight) in flue gas |
| In Fly Ash | 0.07 ppm by weight |

* From Table J-1, Appendix J

** New York City area incinerator

a. Hydrogen Fluoride

Hydrogen fluoride is probably common in incinerator flue gases, but at concentration levels as to be barely detectable. Most likely, these emissions arise from the combustion of fluorinated hydrocarbons such as polytetrafluoroethylene. Because of the highly acidic nature of this gas, high APC collection efficiency is anticipated for wet scrubber systems.

b. Selenium

Selenium appears to a small extent in paper and, as a result of its toxicity, has been of interest. The data in Table V-16 suggest negligible amounts appear in incinerator flue gas streams.

c. Odors

The emission of odorous hydrocarbon materials has, historically, been associated with incinerators. In general, the majority of the odor arises not with the combustion system, but rather, with the collection vehicles, in the pit area where refuse is stored, in the residue quench water system, and at the residue disposal site. Although odor emissions have not been studied in such a way as to allow specification of emission factors, odor emission must be considered in viewing the air pollution potential of municipal incineration.

The methods for odor abatement for an incinerator plant range from positive control (use of special masking agents) to more passive control (enforcement of good housekeeping practices). These methods are discussed in more depth in section VIIC below.

## I. FURNACE EMISSION FACTOR SUMMARY

This section of the report summarizes furnace emission factors for municipal incinerators on two bases:

- Weighted factors with general applicability to the contemporary mix of active U.S. incinerators (an "average" incinerator); and

- Special factors which include the effects of incinerator design and/or the effects of refuse composition on emission.

The "average" emission factors, though of use for rough estimates, tend to over-simplify (as, indeed, does the concept of an emission factor for any complex system). The "average" incinerator factors are derived from the special factors, weighted by the fraction of each incinerator type in the 1968 incinerator inventory.

The special factors reflect a maximum use of available emission data and incorporate engineering judgments based on analysis of the incinerator combustion system. The analysis in preceding sections, however, indicates that a significant and discernible dependency of emission factors on equipment design and refuse composition exists. The factors below suggest the direction and estimate the magnitude of these influences on emission factors.

It should be noted that the emission factors reported in Table V-17 refer to *furnace* emissions. As a consequence, *stack* emissions must be calculated using the efficiency of the air pollution control device associated with the grate/furnace type of interest. Typical APC efficiency values for each pollutant are presented in Table VI-1 and are discussed in depth in section VIIC.

The data, correlations and analysis leading to the emission factors presented in Table V-17 are primitive in comparison to their counterparts for many other air pollution sources. We anticipate and recommend that research be conducted to provide more accurate and reliable values, as a guide in assessing the air pollution problems of incinerators and to stimulate more thorough engineering evaluation of incineration systems. This analysis and the resulting emission factors, however, provide a starting point for both.

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# TABLE V-17

## FURNACE EMISSION FACTOR SUMMARY

| | | Continuous, Refract. Wall | | | | Batch, Refract Wall | | | Continuous, Water Wall[1] | | | | Advanced Concepts[1] | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Incinerator Type | "Average" Incinerator | Rocking Grate | Recip. Grate | Trav. Grate | Grate-Kiln | Circ. | Rectang. | Hearth | Rocking Grate | Recip. Grate | Trav. Grate | Suspension Burning | Slagging Type I | Slagging Type II | Fluid Bed | Pyrolysis |
| Percent of 1968 Inventory[1] | | 22.49 | 8.22 | 19.85 | 6.56 | 23.81 | 3.17 | 15.84 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| Average Capacity (TPD)[1] | 165 | 225 | 225 | 225 | 300 | 130 | 150 | 75 | 350 | 350 | 350 | 300 | 175 | 225 | 60 | 100 |
| **Pollutant** | | | | | | | | | | | | | | | | |
| 1. Mineral Particulate | | | | | | | | | | | | | | | | |
| lbs/ton of refuse[2] | 15.1 | 13.6 | 28.1 | 12.8 | 34.0 | 10.2 | 19.6 | 8.2 | 13.6 | 28.1 | 12.8 | 48.9 | 53.0 | 18.2 | 81.6 | 8.16 |
| lbs/ton of ash (ex. glass, metal) | 277 | 250 | 517 | 236 | 625 | 188 | 360 | 150 | 250 | 517 | 236 | 900 | 975 | 330 | 1500 | 150 |
| 2. Combustible Particulate | | | | | | | | | | | | | | | | |
| lbs/ton of refuse[2] | 4.6 | 3.86 | 3.86 | 3.86 | 2.70 | 4.63 | 5.40 | 5.40 | 2.70 | 2.70 | 2.70 | 1.93 | 1.54 | 3.86 | 0.39 | 0.39 |
| lbs/ton of volatile carbon | 23.7 | 20 | 20 | 20 | 14 | 24 | 28 | 28 | 14 | 14 | 14 | 10 | 8 | 20 | 2 | 2 |
| 3. Carbon Monoxide | | | | | | | | | | | | | | | | |
| lbs/ton of refuse[2] | 34.8 | 29.44 | 29.44 | 29.44 | 20.59 | 35.31 | 41.19 | 41.19 | 20.59 | 20.59 | 20.59 | 14.72 | 11.75 | 29.44 | 2.94 | 2.94 |
| 4. Nitrogen Oxides (as $NO_2$) | | | | | | | | | | | | | | | | |
| lbs/ton of refuse[2] | 3.0 | 3.27 | 3.27 | 3.27 | 3.44 | 2.91 | 3.00 | 2.65 | 3.53 | 3.53 | 3.53 | 3.44 | 3.09 | 3.27 | 2.56 | 2.82 |
| lbs/MM Btu | 0.3 | 0.37 | 0.37 | 0.37 | 0.39 | 0.33 | 0.34 | 0.30 | 0.40 | 0.40 | 0.40 | 0.39 | 0.35 | 0.37 | 0.29 | 0.32 |
| 5. Hydrocarbons | | | | | | | | | | | | | | | | |
| lbs/ton of refuse[2] | 2.7 | 2.26 | 2.26 | 2.26 | 1.58 | 2.72 | 3.17 | 3.17 | 1.58 | 1.58 | 1.58 | 1.13 | 0.90 | 2.26 | 0.23 | 0.23 |
| 6. Polynuclear Hydrocarbons | | | | | | | | | | | | | | | | |
| lbs/ton of refuse $\times 10^3$ [2] | 5.0 | 4.19 | 4.19 | 4.19 | 2.94 | 5.03 | 5.87 | 5.87 | 2.94 | 2.94 | 2.94 | 2.10 | 1.68 | 4.19 | 0.42 | 0.42 |
| lbs/ton of volatile carbon $\times 10^3$ | 25.7 | 21.7 | 21.7 | 21.7 | 15.2 | 26.0 | 30.4 | 30.4 | 15.2 | 14.2 | 15.2 | 10.8 | 8.7 | 21.7 | 2.2 | 2.2 |
| 7. Sulfur Oxides (as $SO_2$) | | | | | | | | | | | | | | | | |
| lbs/ton of refuse[2] | 3.94 | 3.94 | 3.94 | 3.94 | 3.94 | 3.94 | 3.94 | 3.94 | 3.94 | 3.94 | 3.94 | 3.94 | 3.94 | 3.94 | 3.94 | 3.94 |
| lbs/ton of sulfur in refuse | 4000 | 4000 | 4000 | 4000 | 4000 | 4000 | 4000 | 4000 | 4000 | 4000 | 4000 | 4000 | 4000 | 4000 | 4000 | 4000 |
| 8. Hydrogen Chloride | | | | | | | | | | | | | | | | |
| lbs/ton of refuse[2] | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 |
| lbs/ton of PVC resin | 1180 | 1180 | 1180 | 1180 | 1180 | 1180 | 1180 | 1180 | 1180 | 1180 | 1180 | 1180 | 1180 | 1180 | 1180 | 1180 |
| 9. Volatile Metals (as lead) | | | | | | | | | | | | | | | | |
| lbs/ton of refuse[2] | 0.03 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 |
| lbs/ton of metals in refuse | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |

**Notes:**

1. ADL Estimate – Based on total active inventory (Table I-1, Appendix I); used to develop weighting factors to calculate emission factors for "Average" incinerator column.
2. See Appendix C and Table IV-10 for composition of refuse used.

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# VI. AIR POLLUTION FROM INCINERATION IN THE UNITED STATES

# VI. AIR POLLUTION FROM INCINERATION IN THE UNITED STATES

## A. INTRODUCTION

In comparison with the potential air pollution emissions from the power, transportation, and chemical/manufacturing industries in the United States, incineration appears as a relatively unimportant source type. This perspective is deceiving, however, since incinerators are often located in the inner city and are often equipped with inadequate or overloaded control devices. Recent estimates show that municipal incineration in New York City, for example, accounts for almost 20% of the total particulate air pollution within that city. In the localized area immediately surrounding an incinerator, this fall-out of particulate can adversely affect the standard of living, despoiling this limited, but often important, sector of the urban environment.

The substantial growth in the quantity of collected solid waste shown in Chapter IV and the parallel increase likely for incineration suggest that incineration-caused air pollution will tend to increase in the future. To provide an estimate of this increase, an analysis was made to project the magnitude of the incineration air pollution problem through 2000.

The initial step in this process was the characterization of the air pollution potential (furnace emission) from a variety of incinerator types, both existing and proposed. The results of that task are reported in Chapter V (The Nature and Causes of Incinerator Air Pollution) where a tabulation of typical furnace emission factors is presented (Table V-17).

Following the definition of emission factors for each furnace type, a mathematical projection model was prepared to predict future incinerator capacity. Although development of the projections based on definitive plans of municipalities, states, and regional agencies throughout the country was attempted, it was found that insufficient long-range planning had been done to provide reliable projection data. As a result, a mathematical projection model, based on historical incinerator growth but modified to reflect growing solid waste disposal pressures, was prepared.

The comprehensive data bank characterizing the existing incinerator inventory (Appendix I) provided the reference point as to the distribution of active incinerator and air pollution control (APC) system types in the base year of 1968. Estimates of the future growth rate of various incinerator types as well as a companion estimate for air pollution control systems were then made. By combining these assumptions and models, projections of total active incinerator capacity and total furnace and stack emissions were made at various levels of control. Based on the results of an economic analysis (Chapter VII), total investment and operating costs corresponding to these projections were also calculated.

## B. AIR POLLUTION AND MUNICIPAL INCINERATION

### 1. Projection Model

A mathematical model was developed to forecast both municipal incinerator capacity and air pollution load. A computer program was then written to simulate operation of the model. Figure VI-1, showing inputs and outputs, is a generalized flow chart of the model's operation. The following discussion outlines the operation of the model rather than presenting a detailed discussion of the working computer program.

The model uses 1968 as a base year and provides projections for 1970 and subsequently, in five-year increments, to 2000. To account for the differences in refuse composition and other factors across the country, all data banks and projections (where possible) were made on a state-by-state basis. The results presented below, however, are limited to the resulting national totals because of the errors that would be expected for projections for any particular state. These errors, hopefully, are distributed randomly among the states, however, such that the conclusions drawn at the national level should be accurate.

The sources of input data are described below.

#### a. Input Data

*1) Data on State Economic Areas.* As described below, the incineration capacity projections are based upon the population and waste characteristics of the urban areas of the United States. So that a data base descriptive of past and future growth patterns in these areas would be available, the State Economic Areas, or SEA's, were selected. Although incinerators can be – and are being – built outside these regions, we found that the SEA characteristics were acceptable indicators of state-wide incinerator construction. Historical data and forecasts of the population and land area of the SEA's throughout the country were provided through 1985 by the U.S. Bureau of the Census (Schedule D). The data used reflect the most recent definition of SMSA's.* Population projections through 1985 included migrations as well as internal population growth. Projections between 1985 and the year 2000 are based on our own (ADL) demographic estimates.

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*Standard Metropolitan Statistical Area

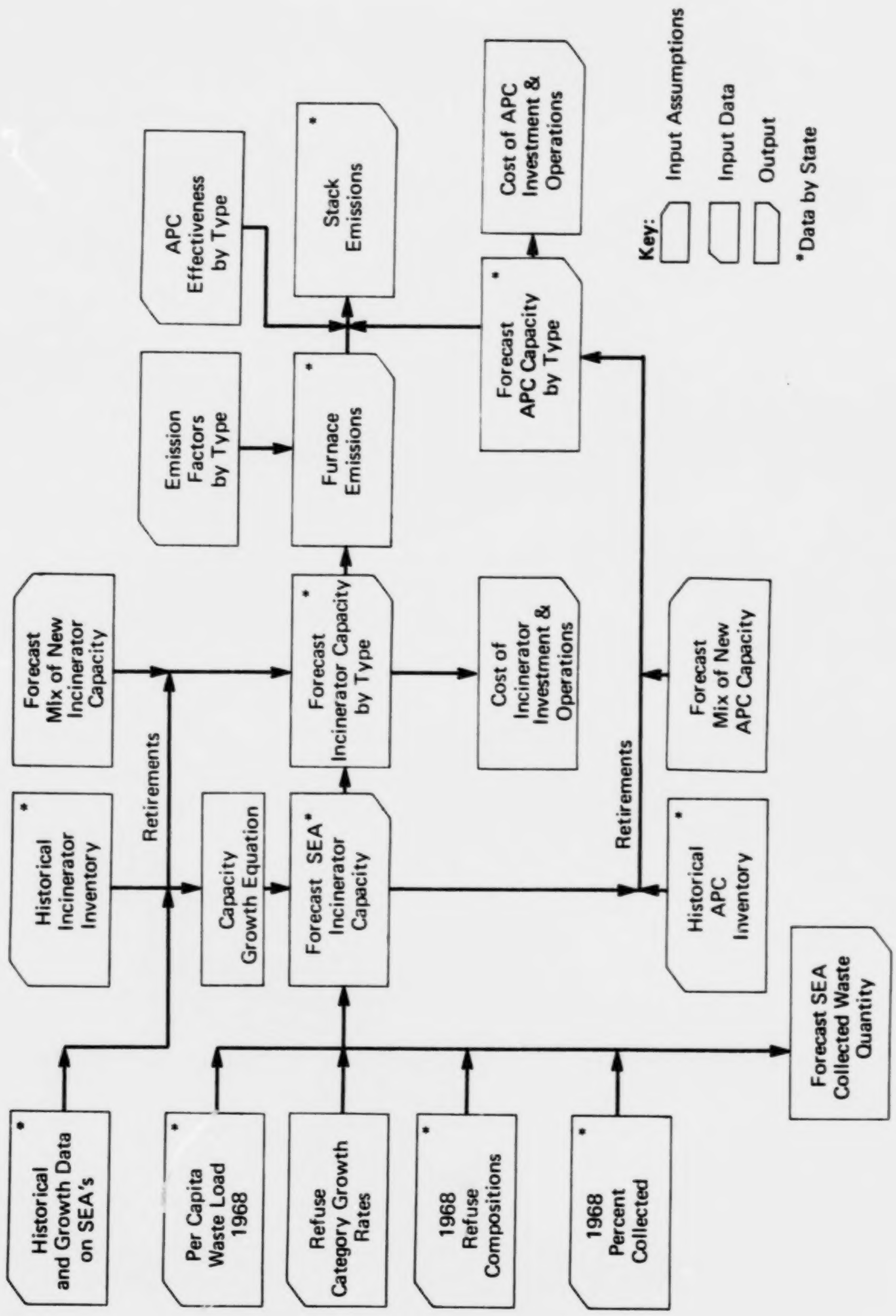
Historical and Growth Data on SEA's *
Per Capita Waste Load 1968 *
Refuse Category Growth Rates
1968 Refuse Compositions *
1968 Percent Collected *
Forecast SEA Collected Waste Quantity
Historical Incinerator Inventory *
Retirements
Capacity Growth Equation
Forecast SEA* Incinerator Capacity
Forecast Mix of New Incinerator Capacity
Forecast Incinerator Capacity by Type *
Cost of Incinerator Investment & Operations
Historical APC Inventory *
Retirements
Forecast Mix of New APC Capacity
Emission Factors by Type
Furnace Emissions *
Forecast APC Capacity by Type *
APC Effectiveness by Type
Stack Emissions *
Cost of APC Investment & Operations
Key:
Input Assumptions
Input Data
Output
*Data by State

FIGURE VI–1 FLOW DIAGRAM OF MODEL

*2) Per Capita Waste Generation (1968).* The per capita waste generation estimates used for the model are reported in Chapter IV and reflect the latest data provided by the Bureau of Solid Waste Management.

*3) Refuse Compositions and Projections (1968).* Refuse composition data for 1968, refuse category growth rates, and the resulting per capita refuse generation multipliers were developed as described in Chapter IV. As described above, the refuse disposal requirement which provides the incentive for new incinerator construction is primarily that of the urban areas, characterized by the SEA's. This quantity of refuse and the per capita generation rates which correspond to it are described in Chapter IV. As part of the model operation, the per capita multipliers for collected solid waste are developed on a state-by-state basis. As will be shown below, these numbers are used in forecasting future incinerator capacity. It should be noted in this regard, however, that the multipliers are ***independent*** of the assumed 1968 per capita waste generation rates.

*4) Percentage of Generated Refuse Collected.* Data on the percent of generated refuse collected in 1968 were as developed above in Chapter IV and reported in Table IV-1. Because we felt that the scope of future refuse collection practices in the urban centers would eventually expand to encompass almost all refuse generated in the household and light-commercial sectors, we assumed that the percent collected, for all states, would increase in a linear fashion from the 1968 levels to 95% collected in 2000.

*5) Historical Incinerator and Incinerator APC Inventory.* The incinerator inventory data, including APC equipment, are presented in Appendix I. This inventory includes all active, municipally owned incinerators. These data were used to develop predictive equations for incinerator capacity, and defined the mix of incinerators and APC systems for 1968, the base year for projection.

*6) Furnace Emission Factors.* Furnace emission factors were either developed from data or estimated for a variety of incinerator types and pollutants. The factors are reported in Table V-17. For purposes of this model, the emission factors reflecting aspects of both incinerator type and refuse compositions were used.

*7) APC Effectiveness.* The pollutant removal effectiveness of several APC systems was estimated in Section V-B. For the purposes of this projection, the average values shown in Table VI-1 were used. These values were selected in recognition of the fact that wide variations in collection efficiency may exist for APC systems acting on different particulate-size distributions and different gaseous pollutant concentrations characteristic of the several incinerator types.

## TABLE VI–1
## AVERAGE CONTROL EFFICIENCY OF APC SYSTEMS

| APC Type | APC System Removal Efficiency (weight percent) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Mineral Particulate | Combustible Particulate(a) | Carbon Monoxide | Nitrogen Oxides | Hydro-carbons | Sulfur Oxides | Hydrogen Chloride | Polynuclear Hydrocarbons(b) | Volatile Metals(c) |
| None (Flue Settling Only) | 20 | 2 | 0 | 0 | 0 | 0 | 0 | 10 | 2 |
| Dry Expansion Chamber | 20 | 2 | 0 | 0 | 0 | 0 | 0 | 10 | 0 |
| Wet Bottom Expansion Chamber | 33 | 4 | 0 | 7 | 0 | 0 | 10 | 22 | 4 |
| Spray Chamber | 40 | 5 | 0 | 25 | 0 | 0.1 | 40 | 40 | 5 |
| Wetted Wall Chamber | 35 | 7 | 0 | 25 | 0 | 0.1 | 40 | 40 | 7 |
| Wetted, Close-Spaced Baffles | 50 | 10 | 0 | 30 | 0 | .5 | 50 | 85 | 10 |
| Mechanical Cyclone (dry) | 70 | 30 | 0 | 0 | 0 | 0 | 0 | 35 | 0 |
| Medium-Energy Wet Scrubber | 90 | 80 | 0 | 65 | 0 | 1.5 | 95 | 95 | 80 |
| Electrostatic Precipitator | 99 | 90 | 0 | 0 | 0 | 0 | 0 | 60 | 90 |
| Fabric Filter | 99.9 | 99 | 0 | 0 | 0 | 0 | 0 | 67 | 99 |

(a) Assumed primarily < 5 microns.

(b) Assumed two-thirds condensed on particulate, one-third as vapor.

(c) Assumed primarily a fume < 5 microns.

*8) Forecast Mix of New Incinerator and APC Capacity.* In use of the model, it is necessary to forecast the distribution or "market share" for new construction among the various alternatives of incinerator and APC system types. The distribution used is shown in Table VI-2. It should be recognized that the values selected are *not* based upon a detailed marketing study of incinerator or APC system penetration of the incinerator marketplace. Rather, they reflect, in broad terms, the anticipated emergence of new concepts and the increasing tendency of communities to select systems with either low air pollution potential, attractive economics, or exceptionally good residue quality. Also inherent in these projections is the assumption that heat recovery will become more important in the latter parts of the century as a consequence of the diminishing availability (and thus higher cost) of fossil fuels. The substantial increases in solid waste load will also tend to justify the larger plants necessary for economical operation with steam generation.

Relative to air pollution control systems, we anticipated that steady movement toward better air pollution control will occur in future years, with some shift away from wet systems and their attendant steam plumes, toward high-efficiency, dry electrostatic precipitators.

No attempt will be made here to defend any one of the values assumed. It is certainly true that any individual familiar with this field could develop an alternative set of assumptions. We felt, however, within the scope of the large number of assumptions necessary for a model such as this, that the resulting emission levels would not be greatly changed by replacement of the values in Table VI-2 with alternative assumptions.

*9) Economic Data.* Table VI-2 also shows assumed average incinerator furnace capacity and consequent investment and total operating costs (excluding APC) for each of the 15 general incinerator types considered (developed in Chapter VII). Operating costs are based on incinerators of the indicated average size operating on a two-shift per day, five-day week basis. APC investment and total operating costs are also shown on an assumed 200 tons/24-hour day (TPD) plant which produces approximately 100,000 cfm of flue gas at 700°F. Investment and operating costs are taken from Chapter VII.

### b. Forecast of SEA Incinerator Capacity

Hopefully predictions of future incinerator capacity could have been based on interviews and opinions of the federal, state, or local agencies now connected with the planning or operation of incinerators. We found, however, conflicting opinions, unresolved decision-makers, and, in many cases, little rational basis for the views being expressed. As a consequence, we had to build a mathematical

# TABLE VI-2

## FORECAST DISTRIBUTION OF NEW CONSTRUCTION AND TYPICAL ECONOMICS AMONG INCINERATOR AND APC CONCEPTS

| | | 1968 Inventory | Time Span '68 - '70 | '70 - '75 | '75 - '80 | '80 - '85 | '85 - '90 | '90 - '95 | '95 - 2000 | Average Capacity[c] (TPD) | Investment ($/TPD)[c,d] | Operating Costs ($/Ton)[d] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| I. | Incineration Systems | | | | | | | | | | | |
| | Type | | | | | | | | | | | |
| 1. | Continuous, Refractory, Rocking Grate | 7.30% | 23% | 24% | 20% | 16% | 13% | 9% | 5% | 225 | $ 6,400 | $ 6.16 |
| 2. | Continuous, Refractory, Reciprocating Grate | 4.20 | 19 | 21 | 18 | 14 | 10 | 6 | 3 | 225 | 6,400 | 6.16 |
| 3. | Continuous, Traveling Grate | 20.87 | 33 | 26 | 20 | 16 | 13 | 9 | 5 | 225 | 6,400 | 6.16 |
| 4. | Continuous, Refractory, Grate & Kiln | 7.05 | 13 | 12 | 15 | 16 | 15 | 10 | 7 | 300 | 5,900 | 5.75 |
| 5. | Batch, Refractory, Circular | 24.30 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 130 | 5,350 | 6.59 |
| 6. | Batch, Refractory, Rectangular Cell | 23.13 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 150 | 5,100 | 7.16 |
| 7. | Batch, Refractory, Hearth | 13.15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 75 | 5,100 | 8.56 |
| 8. | Continuous, Water Wall, Rocking Grate | 0.00 | 0 | 2 | 3 | 3 | 4 | 6 | 8 | 350 | 8,750 | 5.48 |
| 9. | Continuous, Water Wall, Reciprocating Grate | 0.00 | 2 | 3 | 3 | 4 | 6 | 9 | 11 | 350 | 8,750 | 5.48 |
| 10. | Continuous, Water Wall, Traveling Grate | 0.00 | 2 | 4 | 5 | 6 | 8 | 10 | 12 | 350 | 8,750 | 5.48 |
| 11. | Continuous, Water Wall, Suspension Burning | 0.00 | 2 | 5 | 6 | 9 | 9 | 12 | 14 | 300 | 9,350 | 8.06 |
| 12. | Continuous, Slagging Type I[a] | 0.00 | 0 | 2 | 4 | 5 | 7 | 8 | 8 | 175 | 11,800 | 8.83 |
| 13. | Continuous, Slagging Type II[b] | 0.00 | 0 | 1 | 5 | 8 | 10 | 12 | 13 | 225 | 6,400 | 6.16 |
| 14. | Continuous, Fluid Bed | 0.00 | 0 | 0 | 0 | 1 | 2 | 5 | 8 | 60 | 18,400 | 21.23 |
| 15. | Continuous, Pyrolysis | 0.00 | 0 | 0 | 1 | 2 | 3 | 4 | 6 | 100 | 7,250 | 11.94 |
| | Total | 100.00% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | | | |
| II. | APC Systems[e] | | | | | | | | | | | |
| | Type | | | | | | | | | | | |
| 1. | None (flue settling only) | 17.40% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | | 110 | 0.05 |
| 2. | Dry Expansion Chamber | 21.65 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | 110 | 0.05 |
| 3. | Wet Bottom Expansion Chamber | 2.09 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | 170 | 0.14 |
| 4. | Spray Chamber | 12.15 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | | 175 | 0.30 |
| 5. | Wetted Wall Chamber | 16.87 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | 175 | 0.30 |
| 6. | Wetted, Close-Spaced Baffles | 15.84 | 40 | 30 | 20 | 10 | 5 | 0 | 0 | | 215 | 0.32 |
| 7. | Mechanical Cyclone (dry) | 9.22 | 15 | 17 | 20 | 25 | 32 | 35 | 35 | | 340 | 0.77 |
| 8. | Medium-Energy Wet Scrubber | 4.78 | 30 | 35 | 38 | 38 | 33 | 26 | 18 | | 780 | 0.99 |
| 9. | Electrostatic Precipitator | 0.00 | 12 | 16 | 20 | 25 | 28 | 37 | 45 | | 900 | 0.98 |
| 10. | Fabric Filter | 0.00 | 0 | 2 | 2 | 2 | 2 | 2 | 2 | | 900 | 1.10 |
| | Total | 100.00% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | | | |

(a) Slagging Type I comprises a system in which a major part is maintained at a temperature > 2800°F

(b) Slagging Type II comprises a system in which residue fusion takes place almost or entirely as a separate operation

(c) Capacity expressed in units of tons per 24-hour day (TPD)

(d) 1969 dollars, based on assumptions and calculations presented in Section VII - for two shift/day operation

(e) 200-TPD unit, 200% excess air 600°F inlet temperature – equivalent to 100,000 acfm model relating the historical growth in incinerator capacity to factors of population, population density, and waste generated. We fully recognized, however, that using such a model to predict the future, incorporated the broad assumption that the forces acting to create capacity in the past would continue to be the chief forces creating the need for increased capacity in the future.

*1) Mathematical Model.* As a starting point, the 1967 studies carried out under Bureau of Solid Waste Management sponsorship by Combustion Engineering (CE) were reviewed.[1] Of particular importance was their methodology for the projection of national waste reduction capacity. In their study, a regression equation was developed to predict the incinerator capacities of the individual states, based on each state's population and population density. Thus, the overall model was a summation of the capacities of the individual states. The CE researchers found that a very useful term was the factor "population times population density." Since population density was a significant factor in their model, it was felt that rather than use populations and population densities of the entire state, which are subject to "dilution" by large rural areas, better correlations might be found using the population densities of the individual metropolitan districts within the states. To test this hypothesis, and yet avoid having to deal with data for 50 individual states and 253 individual metropolitan districts, seven of the most significant Eastern states* were chosen. Regression equations were developed to correlate the total incinerator capacity for each state, based on state populations and state population densities, and separately, based on Standard Metropolitan Statistical Area (SMSA) populations and population densities.[3] An equation in three variables gave a correlation coefficient squared of 0.85, using state data, and 0.91 using SMSA data** for the same states. The correlation coefficient (r) squared may be roughly interpreted to indicate the fraction of the variation in dependent variable, i.e., incinerator capacity, accounted for by the independent variables. More specifically, $1\text{-}r^2$ is the percent of the variability unassociated with the variables in the regression equation.

The results of this analysis established the SMSA as a better basis for accurate predictions of state incinerator capacity. Further evaluations were then carried out to generate still better mathematical equations. It was found useful to separate the New York City SMSA from New York State, as New York City has a much higher population density and, indeed, has over half of the incinerator capacity of New York State.

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*Connecticut, Florida, New York, Massachusetts, Pennsylvania, Ohio, and Wisconsin.

**Metropolitan data used were the Census Bureau's Standard Metropolitan Statistical Areas (1968).

The best equation developed to predict the incinerator capacity of the seven states, plus Metropolitan NYC, was as follows:

$$y = -352210 + 1.364 \times 10^{-19} \left[ \frac{pop^2 g}{mi^2} \right]^2 + 180.7\,(year) + 0.000065\,(pop)\,(g) \qquad (1)$$

where

y is the total installed capacity in the state (tons/24-hr day –TPD);

g is the solid waste generated per capita per day;

pop is the the total SMSA population in the state; and

$mi^2$ is the total SMSA area in the state (square miles).

The value for "g" used to correlate historical data was taken from the paper by Gilbertson et al.[2] It should be noted that the exact numerical value is not critical in this use, as the majority of the error will be absorbed in the constants. In the use of the large emission model, of which this equation is a part, the 1968 value by Gilbertson (4.75 pounds per capita per day) was multiplied, on a state-by-state basis, by the per capita refuse generation multiplier developed in Chapter IV for prediction years.

The correlation coefficient squared for the above equation was 0.97, indicating that only 3% of the variability was not associated with the three terms included in the equation. Thus encouraged, we assembled data for the incinerator capacity for the New York SMSA and for each of the 50 states, plus the metropolitan district data for each state, including area, population, and population density. Only 43 of the states have municipal incinerators, so that these were used in the regression equations. It was found that when working with the 43 states, it was convenient to work with State Economic Areas (SEA's) defined by the Census Bureau, as opposed to the Standard Metropolitan Statistical Areas, as the Census Bureau breaks the SEA's down by state (whereas, for example, with the SMSA's, Cincinnati would appear only as Ohio metropolitan, including Covington, Kentucky). All subsequent equations, therefore, are based on SEA data and projected data.

With Equation (2) below, using only three variables, the capacity of New York and the 43 individual states could be predicted to the extent of a correlation coefficient squared of 0.80:

$$y = -140235 + 1.162 \times 10^{-19} \left[ \frac{pop^2 g}{mi^2} \right]^2 + 71.6\,(year) + 0.000517\,(pop) \qquad (2)$$

This correlation is not so good as that for the seven homogeneous states used previously because of the much greater diversity in incinerator capacities, population, and population densities. The standard error of estimate, however, is only 960 TPD per state. For the sum total capacity of the U.S., the error of estimate would amount to:

$$\frac{960}{\sqrt{43}} \times 43 = 6250 \text{ TPD per year} \qquad (3)$$

A final modification of the equation is necessary in that the emission model uses 1968 as the base year to make use of the most current figures for existing incinerator capacity. Population estimates used in the model are interpolated to 1968 from census figures and estimated growth rates. The first year to which the model projects is 1970; thus the modified equation reads:

$$y = -141052 + 1.162 \times 10^{-19} \left[ \frac{\text{pop}^2 g}{\text{mi}^2} \right]^2 + 71.6\,(\text{year}) + 0.000517\,(\text{pop}) \qquad (4)$$

This capacity projection equation is independent of capacity already existing in each state. In practice, the model must account for this capacity.

Equation (4) is a useful tool for estimating the installed incinerator capacity by state and by year. Examination of the variables suggests a strong dependency upon the refuse generation density (g times population density) compounded with land availability (population density) and a measure of the total size of the municipality (population). The dependency upon "year" is an indication of unknown effects; the equation demands that 71 TPD be installed every year in every state.

The model has a singular deficiency, however, in that it assumes that no new social, economic, or technical factors will modify trends in the future. Thus, although the model appears satisfactory for interpolation, it poses risks for extrapolation. As a result, multipliers were assumed which, for states where it was felt that unusual pressures would be felt, would act directly on "y" to increase the calculated capacity. These multipliers, or accelerated incinerator growth factors, were selected based on assessment of the following parameters:

- Estimates of current percent collected (Table IV-1) contrasted with the assumed 95% collected in the year 2000;
- Judgment as to the availability of landfill sites near the SEA population centers;

- Judgment as to the rate at which open burning or other offensive alternative waste disposal practices would be discontinued;

- Judgment as to the tolerance of the SEA's for incinerators, no matter how well-designed or operated (California only).

The resulting accelerated incinerator growth factors are shown in Table VI-3.

*2) Steps in Computation*

*a) Weighted Mean Age.* A meaningful projection of future incinerator capacity must allow for the retirement of old plants and equipment. The model retires equipment, on a state-by-state basis, after a 35-year lifetime. Over the duration of the forecast (32 years), therefore, no "new capacity" would be retired. The retirement operation was thus only affecting the base year incinerator and APC inventory. Because of limitations in the available computer memory size and the large storage required for interactive retirement (i.e., the proper APC system must be retired from the APC inventory when its incinerator is retired), it was felt acceptable to evaluate the weighted age of the various APC types and incinerator types within a state's base year inventory, and then to effect retirement of the *block* of capacity 35 years after that year.

The weighted mean age is derived by multiplying an incinerator's age in relation to the base year by its total rated capacity. Once total TPD years for each incinerator type in a state are accumulated, this figure is divided by the total TPD, giving a weighted mean age. The age of the incinerator in terms of air pollution control equipment capacity is calculated similarly.

*b) Capacity Equation.* The total capacity for each state and projection year is calculated using the equation described above. The historical values used for "g" in the equation derivation were those of Gilbertson et al.[2] It was felt, however, that it would be an unnecessary simplification to continue with this somewhat outdated prediction through the year 2000, but that it would be unwise to use the calculated per capita daily refuse burden (including changes in percent collected, etc.) developed above. It was decided, therefore, to use the Gilbertson value for 1968 (4.75 pounds per capita per day) and to use the per capita waste generation multipliers, on a state-by-state basis, to modify this parameter in the projection years.

*c) Incremental Capacity.* The total incremental capacity for each projection year and state is divided into national average market shares (Table VI-2) of each incinerator and air pollution control device type. This is then added to the previous projection year's capacity of that particular type. Any retirements which

## TABLE VI–3

## ACCELERATED INCINERATOR GROWTH FACTOR ESTIMATES

| State | Time Span | | | | | | |
|---|---|---|---|---|---|---|---|
| | '68 - '70 | '70 - '75 | '75 - '80 | '80 - '85 | '85 - '90 | '90 - '95 | '95 - 2000 |
| **HEW Region I** | | | | | | | |
| Connecticut | 1.0 | 1.03 | 1.06 | 1.10 | 1.13 | 1.18 | 1.23 |
| Maine | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Massachusetts | 1.0 | 1.03 | 1.06 | 1.10 | 1.13 | 1.18 | 1.23 |
| New Hampshire | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Rhode Island | 1.0 | 1.05 | 1.10 | 1.15 | 1.18 | 1.22 | 1.25 |
| Vermont | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| **HEW Region II** | | | | | | | |
| Delaware | 1.0 | 1.03 | 1.08 | 1.13 | 1.16 | 1.18 | 1.20 |
| New Jersey | 1.0 | 1.03 | 1.08 | 1.13 | 1.16 | 1.18 | 1.20 |
| New York (ex city) | 1.0 | 1.02 | 1.06 | 1.09 | 1.11 | 1.13 | 1.15 |
| Pennsylvania | 1.0 | 1.03 | 1.05 | 1.07 | 1.08 | 1.09 | 1.10 |
| New York City | 1.0 | 1.05 | 1.10 | 1.15 | 1.18 | 1.22 | 1.25 |

## TABLE VI–3 (Continued)

| State | Time Span | | | | | | |
|---|---|---|---|---|---|---|---|
| | '68 - '70 | '70 - '75 | '75 - '80 | '80 - '85 | '85 - '90 | '90 - '95 | '95 - 2000 |
| **HEW Region III** | | | | | | | |
| Kentucky | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Maryland | 1.0 | 1.05 | 1.10 | 1.15 | 1.18 | 1.22 | 1.25 |
| North Carolina | 1.0 | 1.00 | 1.00 | 1.01 | 1.02 | 1.04 | 1.05 |
| Virginia | 1.0 | 1.02 | 1.03 | 1.05 | 1.08 | 1.10 | 1.13 |
| West Virginia | 1.0 | 1.02 | 1.03 | 1.05 | 1.08 | 1.10 | 1.13 |
| **HEW Region IV** | | | | | | | |
| Alabama | 1.0 | 1.02 | 1.03 | 1.04 | 1.06 | 1.08 | 1.10 |
| Florida | 1.0 | 1.03 | 1.07 | 1.11 | 1.15 | 1.19 | 1.23 |
| Georgia | 1.0 | 1.00 | 1.01 | 1.02 | 1.02 | 1.04 | 1.05 |
| Mississippi | 1.0 | 1.00 | 1.01 | 1.02 | 1.02 | 1.04 | 1.05 |
| South Carolina | 1.0 | 1.02 | 1.03 | 1.05 | 1.08 | 1.10 | 1.13 |
| Tennessee | 1.0 | 1.01 | 1.02 | 1.04 | 1.07 | 1.11 | 1.15 |
| **HEW Region V** | | | | | | | |
| Illinois | 1.0 | 1.01 | 1.02 | 1.04 | 1.07 | 1.11 | 1.15 |
| Indiana | 1.0 | 1.01 | 1.02 | 1.04 | 1.07 | 1.11 | 1.15 |
| Michigan | 1.0 | 1.04 | 1.09 | 1.13 | 1.18 | 1.24 | 1.30 |
| Ohio | | | | | | | 1.20 |
| Wisconsin | 1.0 | 1.02 | 1.03 | 1.05 | 1.08 | 1.10 | 1.13 |

## TABLE VI–3 (Continued)

| State | Time Span | | | | | | |
|---|---|---|---|---|---|---|---|
| | '68 - '70 | '70 - '75 | '75 - '80 | '80 - '85 | '85 - '90 | '90 - '95 | '95 - 2000 |
| **HEW Region VI** | | | | | | | |
| Iowa | 1.0 | 1.0 | 1.0 | 1.0 | 1.01 | 1.02 | 1.03 |
| Kansas | 1.0 | 1.0 | 1.01 | 1.03 | 1.05 | 1.07 | 1.10 |
| Minnesota | 1.0 | 1.02 | 1.05 | 1.08 | 1.11 | 1.14 | 1.18 |
| Missouri | 1.0 | 1.02 | 1.06 | 1.09 | 1.11 | 1.13 | 1.15 |
| Nebraska | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| North Dakota | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| South Dakota | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| **HEW Region VII** | | | | | | | |
| Arkansas | 1.0 | 1.0 | 1.0 | 1.0 | 1.01 | 1.02 | 1.03 |
| Louisiana | 1.0 | 1.0 | 1.01 | 1.03 | 1.05 | 1.07 | 1.10 |
| New Mexico | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Oklahoma | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Texas | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |

## TABLE VI–3 (Continued)

| State | Time Span | | | | | | |
|---|---|---|---|---|---|---|---|
| | '69 - '70 | '70 - '75 | '75 - '80 | '80 - '85 | '85 - '90 | '90 - '95 | '95 - 2000 |
| **HEW Region VIII** | | | | | | | |
| Colorado | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Idaho | 1.0 | 1.03 | 1.05 | 1.07 | 1.08 | 1.09 | 1.10 |
| Montana | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Utah | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Wyoming | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| **HEW Region IX** | | | | | | | |
| Alaska | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Arizona | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| California | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Hawaii | 1.0 | 1.03 | 1.07 | 1.11 | 1.15 | 1.19 | 1.23 |
| Nevada | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Oregon | 1.0 | 1.02 | 1.04 | 1.07 | 1.10 | 1.13 | 1.16 |
| Washington | 1.0 | 1.02 | 1.04 | 1.07 | 1.10 | 1.13 | 1.16 |

occur between the previous and current projection year are added to the incremental capacity and, similarly, divided into market shares and added to existing capacity. In some cases, the incinerator capacity which is present in the base year (1968) exceeds the projection for that state in a future year. This is allowed to stand as is until future capacity projections exceed this capacity or until retirement opens new construction opportunities. The model thus provides capacity figures by year and state with regional and national totals for each type of incinerator and each type of air pollution control device. It should be noted that the model does not attempt to match APC system to incinerator type. Instead, as with incinerator capacity, new construction capacity is spread among the various alternatives in accord with the assumed national market share distributions.

### c. Pollution Load Estimates

*1) Furnace Emissions.* In practice, incinerator furnaces operate on many different schedules, depending upon the disposal needs of the community, plant maintenance practices, and the like. Based upon the results of a questionnaire solicitation made as a part of this program (see Appendix I), 87 plants average 56% on-line (4900 hrs/yr), but record 43% effective use at their *rated* capacities. The standard deviation of the latter value was 30%. Because of the limited, and perhaps unrepresentative, depth of this sample, the percent use based on rated capacity was not introduced as a working constant in the calculation of furnace emission, but rather the model assumes operation at capacity, 24 hours per day for 365 days per year. Subsequent to the computer calculations, the resulting emission values were corrected by an operating factor at 50% for the base year (1968) and linearly interpolated to 65% in the year 2000.

Ten pollutants were considered. Each has an emission factor expressed in pounds of pollutant per ton of refuse or selected material within the refuse. An exception is the emission factor for nitrogen oxides which is in units of pounds per million Btu heat release. Pollutant emission calculations may be considered as one of three types. Type A factors are those which are functions of furnace type only, including carbon monoxide and hydrocarbons. Type B emission factors are functions of the composition of refuse only, independent of incinerator type. These include sulfur dioxide, hydrogren chloride, and volatile metals. Type C emission factors are functions of both incinerator type and refuse composition. These include mineral particulates, combustible particulates, nitrogen oxides, and polynuclear hydrocarbons. Furnace emissions are thus calculated for each state based on the state's unique refuse composition, total incineration capacity, and incinerator mix using the emission factors given in Table V-17.

*a) Mineral Particulates.* On a dry basis, the products of the weight fraction and percent ash of each refuse component (excluding metal and glass) is summed.

This factor times the emission factor and the quantity of refuse burned for each incinerator type (active capacity) provides the total pollutant emissions.

*b) Combustible Particulates and Polynuclear Hydrocarbons.* On a dry basis, the products of weight fraction and volatile carbon fraction of each refuse component are summed. This factor times the emission factor and active capacity for each incinerator type provides the total emissions for each of these pollutants.

*c) Carbon Monoxide and Hydrocarbons.* The total emission of these pollutants is the sum of the products of active capacity (regardless of composition) in each incinerator type and the emission factors for each incinerator type.

*d) Nitrogen Oxides (as nitrogen dioxide).* On a dry basis, the products of weight fractions and the heating value (Btu/lb) of each refuse component are summed. This factor times the emission factor and active capacity for each incinerator type provides the total pollutant emissions.

*e) Sulfur Oxides (as sulfur dioxide).* On a dry basis, the products of the weight fraction of each refuse component and the oxidizable sulfur content of that component are summed. The pollutant emission is this factor times the total active capacity (regardless of incinerator type) at the emission rate of 4000 pounds per ton of sulfur.

*f) Hydrogen Chloride and Metals.* For hydrogen chloride, the polyvinyl chloride (PVC) component of the plastics portion of refuse is assumed to yield HCl quantitatively at a rate universal to all incinerator types. Similarly for metals, the percent volatile metals in the metals portion of refuse is emitted at the same rate for all incinerators.

*2) Stack Emissions.* The model is provided with air pollution control removal efficiency values for each of 10 types of air pollution control equipment in dealing with the 10 pollutants (Table VI-1). The model calculates the capacity weighted fraction of the total national capacity for each control device from the previously calculated capacity figures. The APC removal efficiencies for each pollutant by equipment type are multiplied by the market share of each equipment type and summed to a weighted national average efficiency. These national averages are applied to the incinerator emissions on a state-by-state basis to provide stack emissions for each of the pollutants. Again, the model provides these data by state with regional and national totals for the base year and each projection year. The output is in tons per year of each of the nine pollutants emitted at an operating efficiency of 50% in 1968 (based on rated capacity), increasing linearly to 65% in 2000.

### d. Investment and Total Operating Costs

The model is provided with unit costs, in dollars per TPD and dollars per ton burned, for both capital investment and day-to-day operation of each type of incinerator and APC equipment (Table VI-2). The unit costs are multiplied by the appropriate installed capacity figures and summed to national totals for each projection year. The costs thus calculated are in 1969 dollars. As above, operating costs are based on an operating efficiency varying from 50% to 65% (of rated capacity) over the 32-year period.

## 2. Projection Results – General

The results of the computer-implemented mathematical model provide insight into the scope of the incinerator air pollution problem in forthcoming years. It is appropriate, however, before presenting the results of these calculations, to summarize the applicability and the limitations inherent in the model itself, in the data bank supporting the model, and thus in the credibility of the model output.

Strictly, the model only applies to the SEA areas, and for domestic/commercial waste. All data defining the parameters in the equations for incinerator capacity, solid waste generation rate, and the fraction of generated waste which is collected refer to the SEA's and domestic/commercial refuse only. It should be noted, however, that the incinerator capacity equation was a correlation of *total* state-installed capacity data, and not only of the SEA areas. It is felt, therefore, that the sum of the state-by-state projections are valid estimates of the total *national* installed capacity and resulting air pollution emissions. Calculations of collected solid waste, however, since they are based on SEA population and collection data, only apply to the SEA's.

Restricting the model input data and functional form to consider only domestic/commercial waste appears a possibly more serious shortcoming. The need for systems to incinerate industrial solid waste, municipal and industrial sewage sludges, waste oils and solvents, and some agricultural wastes is growing. The impact of this need upon municipal decision-makers as regards installation of additional incinerator capacity is unknown. Alternatives such as the use of on-site landfill or incineration, privately operated incinerators, or integrated waste disposal facilities are competing, and often more favorable, solutions. Such waste disposal requirements, however, would almost always tend to increase the installed municipal incinerator capacity (and air pollution emissions) over that calculated by the model. It should be noted in this regard that the increase would not be a scalar multiple of the calculated emissions as a consequence of the substantial differences in the composition of these wastes compared to domestic/commercial waste. One might expect, for example, a greater hydrogen chloride emission due to the large quantity of polyvinyl chloride wastes generated in many industrial plants.

The data input to the model appears sound as regards the present and forecast SEA populations and the 1968 incinerator and APC inventory. Uncertainties exist, however, in the present and forecast solid waste quantity and composition, the fraction of generated waste which is and will be collected, and future trends in incinerator and APC system selection. It is felt, however, that the assumptions made to implement the model were reasonable and that the "answers" would not be greatly affected by moderate changes in these assumptions.

In general, therefore, the model results would appear somewhat conservative as regards incinerator capacity and furnace emissions. The results on stack emissions are slightly more conservative (especially in the near-term) as the model does not provide explicitly for up-grading APC equipment on existing plants. A quantitative estimate of this conservatism is difficult, however.

### 3. Projection Results – Incinerator Capacity

The lower line of Figure VI-2 was developed from the historical model. It can be seen that the installed incinerator capacity is expected to increase almost four-fold over the next 30 years at an average rate of approximately 7000 TPD/year. Incorporation of the accelerated incinerator growth factors on a state-by-state basis produces the upper curve of Figure VI-2. The net effect of these factors was to increase the year 2000 projections by 40,000 TPD. It can also be seen that, based on the accelerated incinerator growth factors selected, the primary impact of these modifiers occurs in the latter half of the 30-year period.

Figure VI-3 indicates projections of the fraction of collected waste which will be incinerated. To develop this plot, assumptions as to the fraction of the total installed plant capacity used were required. Based on the questionnaire returns reported in Appendix I, an average use factor of 50% (based on rated capacity) was assumed for 1968. This corresponds to 20% incineration of the SEA collected solid waste in the year 1968. This figure is approximate, however, as it assumes that *all* incinerators are located in SEA areas, an assumption not implicit in the incinerator capacity projection model.

In the future, the increased use of waterwall boiler designs and the increasing quantity of collected solid waste will probably act to increase the average plant use factor. For the purposes of this projection, a 65% operating factor was used for the year 2000, with linear interpolation between this value and the 50% selected for 1968 for intermediate years. Based on the historical model of incinerator growth, the increasing plant factor and capacity result in slightly over 23% incineration increase by the year 2000. The augmented incineration growth increases the percent incinerated to approximately 27% by the year 2000.

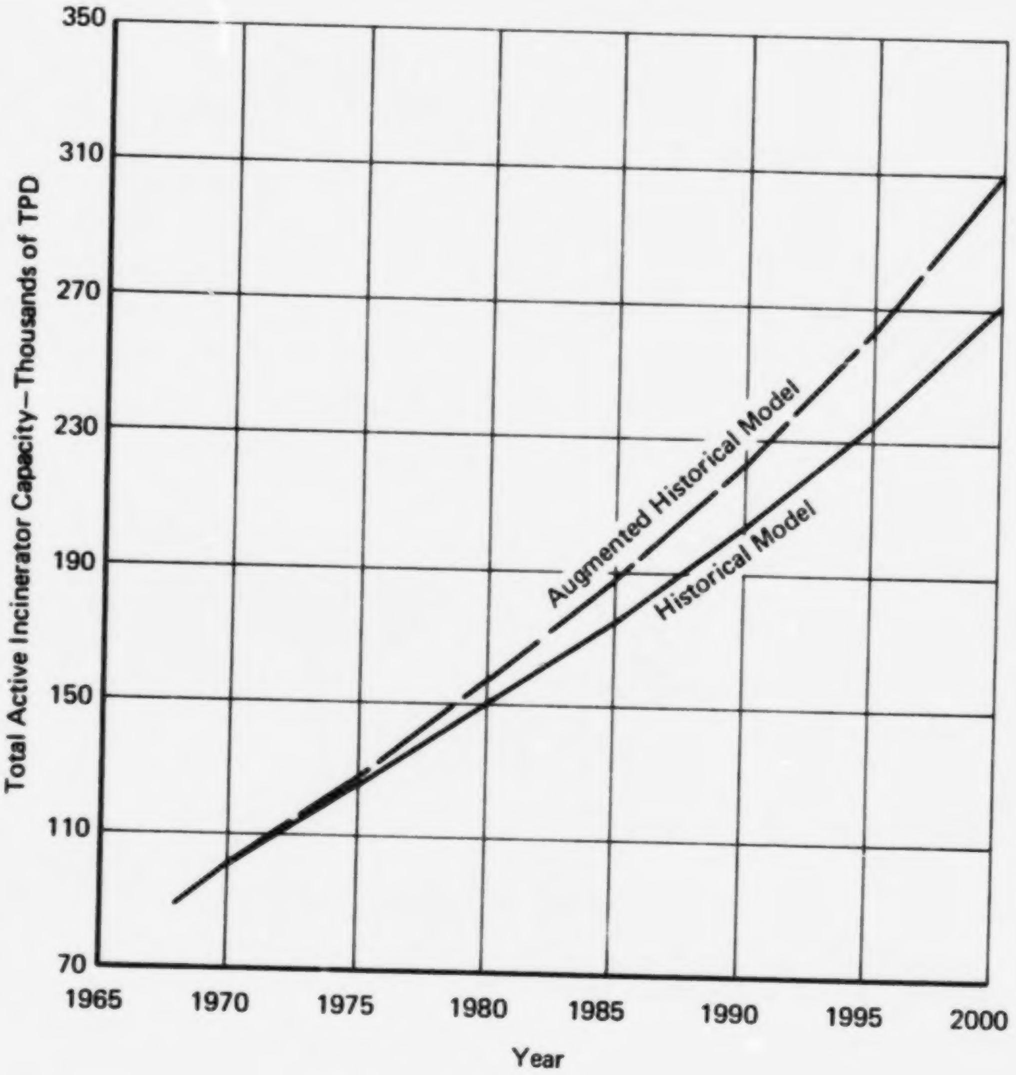


FIGURE VI–2 PROJECTIONS OF FUTURE ACTIVE INCINERATOR CAPACITY

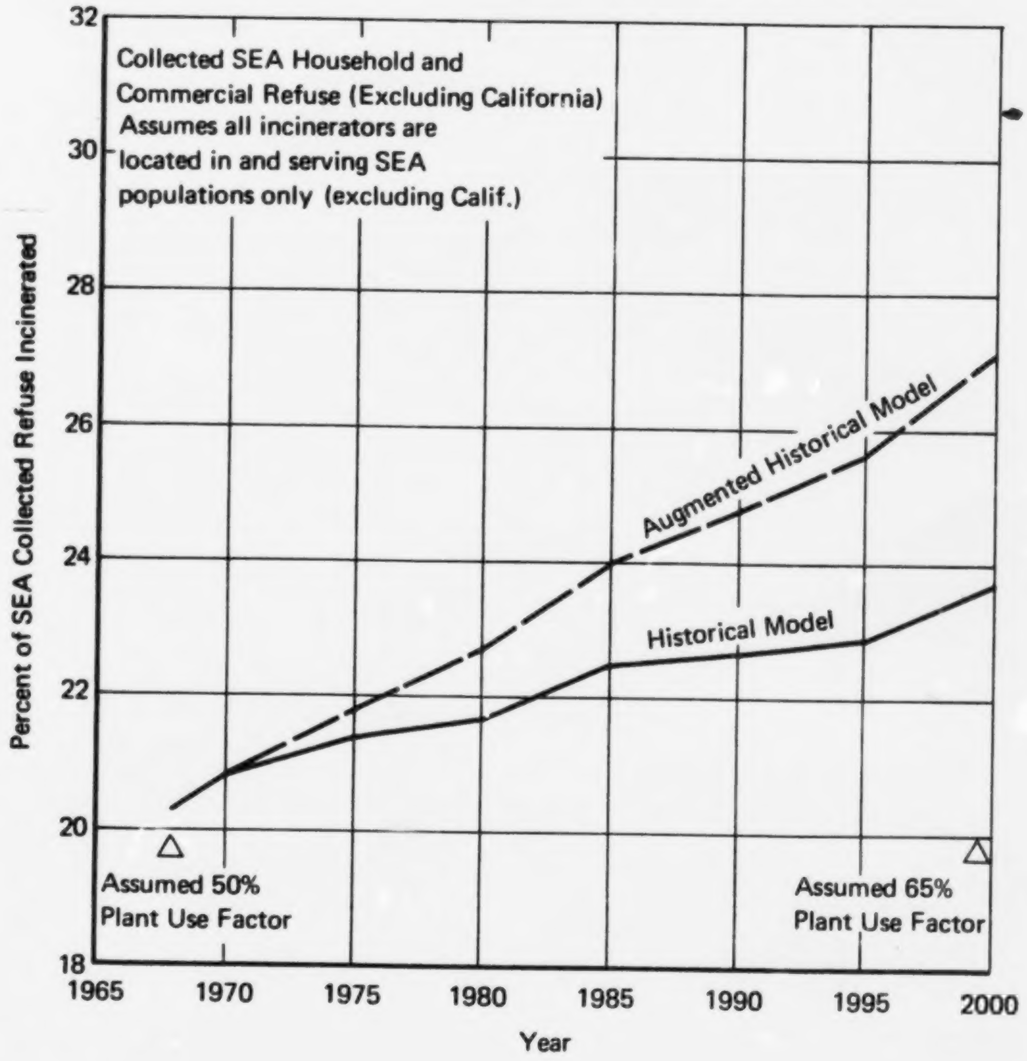


FIGURE VI–3 PROJECTIONS OF FRACTION OF SEA-COLLECTED WASTE INCINERATED

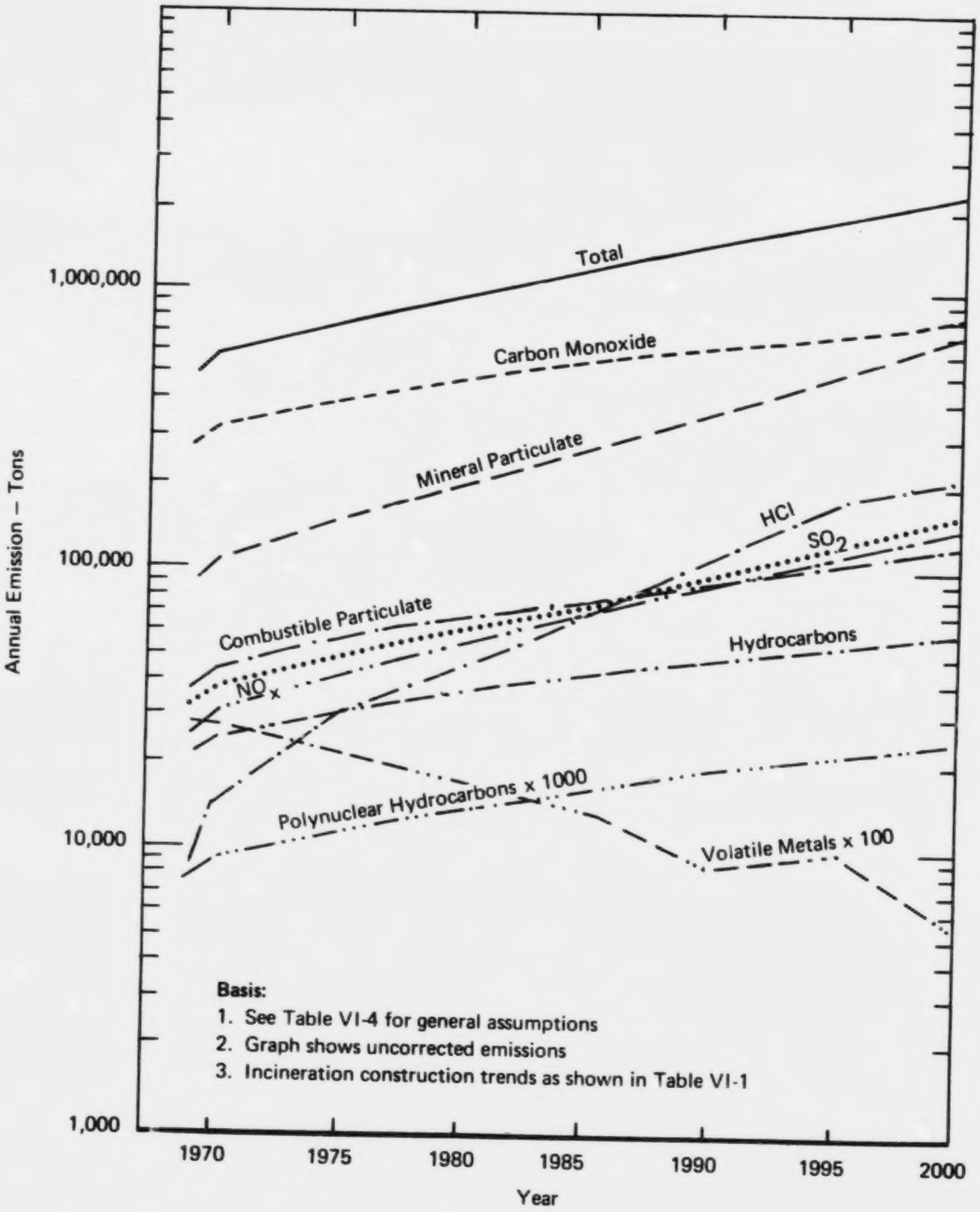
As described above in the discussion of the model, it was felt that the historical model would underestimate the future growth rate of municipal incineration. As a result, *all* computations presented below regarding furnace and stack emissions and incinerator and APC system costs were developed using the growth trends incorporating the accelerated growth factors.

### 4. Projection Results – Furnace Emissions

Based on the use of the model, with the assumptions indicated in Table VI-2 and the accelerated incinerator growth rates, the total uncontrolled furnace emission rates shown in Figure VI-4 were developed. In this and *all* subsequent emission plots, a 50% equipment use factor was assumed for 1968 and 65% for the year 2000 (based on rated capacity) with linear interpolation for the intermediate years. The use factor estimate was based on data reported in Appendix I and judgments regarding future trends in equipment use. To clarify the assumptions implicit in this and the following graphs, Table VI-4 provides a summary of the basis for each graphical presentation.

Figure VI-4 indicates that current total furnace emissions from municipal incinerators approximate 580,000 tons per year. The majority of this emission is carbon monoxide (320,000 tons per year), followed by mineral particulate at about 107,000 tons per year. If projected into the future, the calculations suggest a decrease in carbon monoxide emissions relative to mineral particulate and a general decrease in the average amount of carbon monoxide generated per ton burned. Mineral particulate furnace emissions, however, will increase over five-fold in this time period, the more rapid rate arising from the introduction of high emission rate concepts, such as suspension burning and fluidized bed units.

The emissions of combustible pollutants (carbon monoxide, hydrocarbons, polynuclear hydrocarbons, and combustible particulate), however, could be reduced over the projection period to a greater extent than is shown in Figure VI-4. These pollutants will burn out rapidly within an incinerator if the flue gases are well-mixed. New design concepts and improved operating practices to enhance and assure mixing (discussed in Chapters V, VII-C, and Appendix H), if implemented in both existing and new plants, could reduce emissions of these pollutants by at least 25-50%. The opportunity and incentive for such improved combustion efficiency are particularly evident for steam-raising units. For these plants, improved combustion may reduce boiler dimensions (cost) and improve thermal efficiency. The availability of steam (for steam-jet-induced mixing in the combustion volume) with boiler systems may also be exploited. Specific research and development programs to provide such improved design and operating criteria are presented in Chapter VIII.



**Basis:**

1. See Table VI-4 for general assumptions
2. Graph shows uncorrected emissions
3. Incineration construction trends as shown in Table VI-1

FIGURE VI–4 TOTAL ANNUAL FURNACE EMISSION ESTIMATES FOR U.S. MUNICIPAL INCINERATION SYSTEMS

## TABLE VI–4
## ASSUMPTIONS INCORPORATED IN AIR POLLUTANT EMISSION GRAPHS

I. **Assumptions Applicable to All Graphs**

A. All graphs are based on the total national municipal incinerator capacity projections incorporating the augmented incinerator growth factors.

B. All graphs are based on operation of active incinerators at 50% of rated daily capacity in 1968 and 65% in 2000 with linear interpolation for the intervening years.

C. All graphs assume no upgrading of existing units, either by APC system improvement or changes in operating practices.

D. Graphs labeled "decay" describe the situation where no new plants are built in any of the projection years. Thus, as individual plants attain their 35-year life, they are retired without replacement. Such graphs thus show the contribution of equipment which was in service in 1968 to air pollution emissions in the future.

II **Specific Assumptions**

| | | **Assumed New Plant Construction Trends** | |
|---|---|---|---|
| **Figure No.** | **Subject** | **Incinerator Furnace** | **APC Systems** |
| VI–4 | Furnace Emissions(1) | Base(5) | – |
| VI–5 | Furnace Emissions(1) | Accelerated New(6) | – |
| VI–6 | Stack Emissions(2) | Base(5) | Base(5) |
| VI–7 | Stack Emissions(2) | Accelerated New(6) | Base(5) |
| VI–8 | Stack Emissions(2) | None(7) | None(7) |
| VI–9 | Stack Emissions(2) | Base(5) | 52% Efficiency (new)(9) |
| VI–10 | Stack Emissions(2) | Base(5) | 70% Efficiency (new)(9) |
| VI–11 | Stack Emissions(2) | Base(5) | 90% Efficiency (new)(9) |
| VI–12 | Capital Investment(3) | All(8) | All(9) |
| VI–13 | Operating Cost(4) | All(8) | All(9) |
| VI–14 | Stack Emissions (Particulate)(2) | Base(5) | All(9) |
| VI–15 | Stack Emissions (combustible and particulate)(2) | All(8) | Base(5) |

**Notes:**

(1) Uncorrected emissions based on emission factors from Table V–
(2) Emissions after APC device based on efficiencies from Table VI–1.
(3) Net value (1969 dollars) of active capacity – investment from Table VI–2.
(4) Total annual operating cost, including capital charges at 50-65% operating factor (see text).
(5) Future incinerator or APC construction trends prescribed as in Table VI–1.
(6) Future incinerator construction trends accelerate use of new concepts as in Table VI–5.
(7) No new construction after 1968; curves show retirement of 1968 active capacity.
(8) Base (5) and accelerated use (6) construction patterns shown.
(9) All future APC systems restricted to yield specified particulate removal efficiency.

The majority of the remaining pollutants is generated at relatively low concentrations. Their emission rates generally increase parallel to the total pollution emission rate. Hydrogen chloride and volatile metals are exceptions. Hydrogen chloride emissions increase at a substantially higher rate than other pollutants, primarily due to growth in the use of polyvinyl chloride packaging material. Volatile metal emission (lead) decreases with time, primarily due to the decreased use of lead-bearing soldered tin cans for packaging applications.

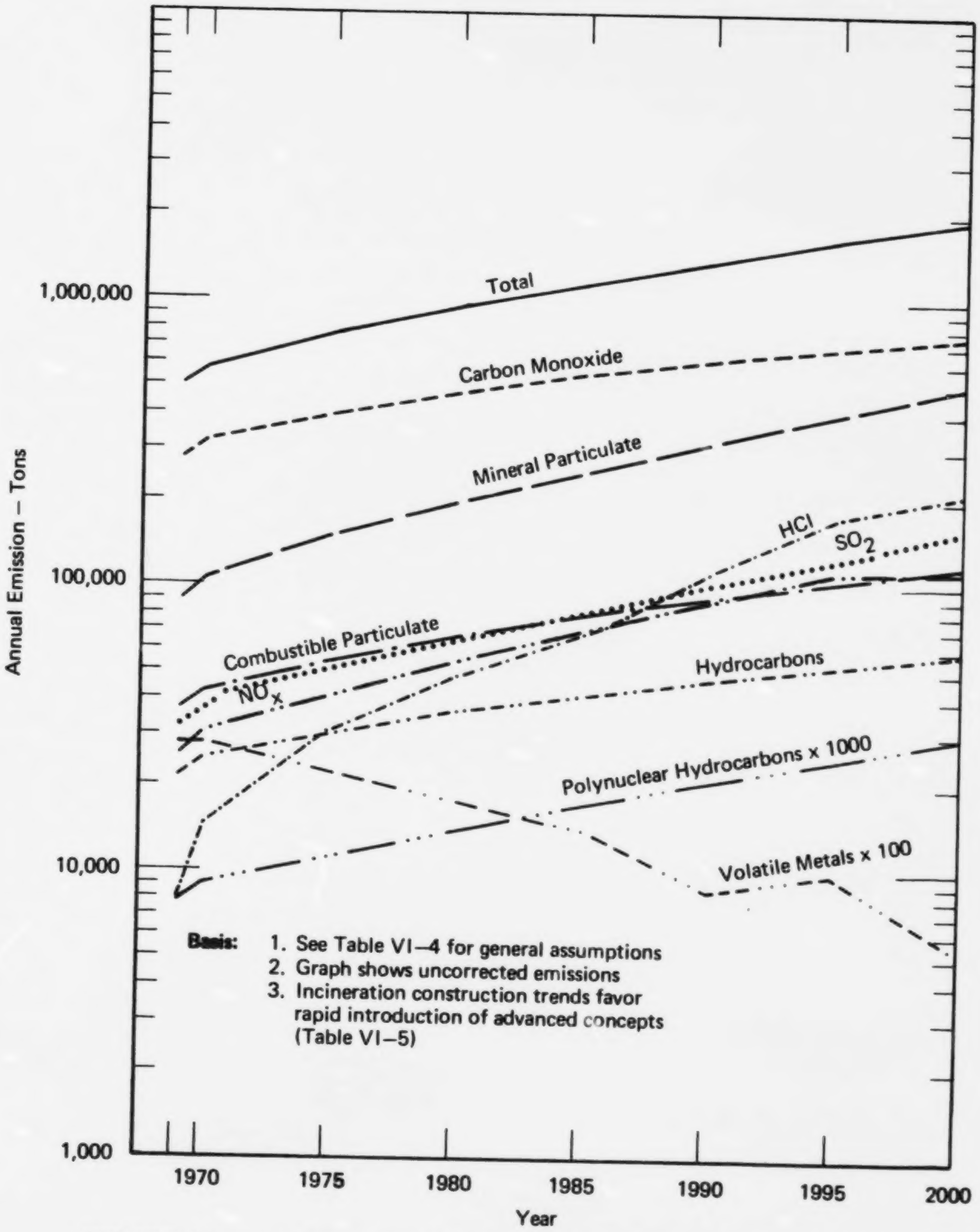
Figure VI-5 indicates the estimated total emissions assuming the rapid introduction of advanced incineration concepts, particularly pyrolysis. The assumed incinerator construction trends are shown in Table VI-5. A modest (6%) reduction in carbon monoxide emissions and in total pollutant emissions (13%) may be noted by the year 2000 in comparison to the previous calculations. The mineral particulate emissions, however, are significantly reduced (from 710,000 tons per year to 510,000 tons per year – a 28% reduction) over the same time-period. This reflects the increased use of pyrolysis units on furnace emissions. As described above, the combustible pollutant emissions could be reduced in this case also by development of improved combustion system designs and operating practices.

### 5. Projection Results – Stack Emissions

Following the rationale presented in the model description, the data for Figure VI-6 were developed to show the total stack emissions, reflecting the effect of the APC systems on the furnace emissions presented above. The construction trends for new APC systems used in these calculations are as shown in Table VI-2. In contrast with the furnace emission values shown in Figure VI-4, it can be seen that the mineral particulate emission levels off about 1990. Based on the assumption of an increase and then a decrease in the use of wet collectors, the growth rate of total hydrogen chloride emissions is at first slowed, but then accelerates rapidly.

Figure VI-7 shows the total stack emission assuming the rapid implementation of advanced incineration concepts. It can be seen that the mineral particulate emission now peaks in 1990 and that the peak emissions are approximately 16% lower than for the reference case (Figure VI-6).

Figure VI-8 shows the decline in pollutant emissions (as a result of plant retirement) from existing incinerators, assuming no new construction after 1968. This graph is presented to show the effect of existing plants on stack emissions in the future. It can be seen that, based on the assumption of a 35-year plant life, significant decreases in the contribution to national emissions from existing units do not begin until approximately 1985. Figure VI-8 may be used, in conjunction with the other plots presented, to discount the effect of existing capacity in



**Basis:**
1. See Table VI–4 for general assumptions
2. Graph shows uncorrected emissions
3. Incineration construction trends favor rapid introduction of advanced concepts (Table VI–5)

FIGURE VI–5 TOTAL ANNUAL FURNACE EMISSION ESTIMATES FOR U.S. MUNICIPAL INCINERATOR SYSTEMS ASSUMING RAPID INTRODUCTION OF ADVANCED TECHNIQUES

## TABLE VI–5
## ASSUMED DISTRIBUTION OF NEW CONSTRUCTION AMONG INCINERATOR CONCEPTS FOR RAPID IMPLEMENTATION OF ADVANCED CONCEPTS

| | Incineration System Type | 1968 Inventory | Time Span '68 - '70 | '70 - '75 | '75 - '80 | '80 - '85 | '85 - '90 | '90 - '95 | '95 - 2000 |
|---|---|---|---|---|---|---|---|---|---|
| 1. | Continuous, Refractory, Rocking Grate | 7.30% | 29% | 24% | 18% | 15% | 10% | 7% | 1% |
| 2. | Continuous, Refractory, Reciprocating Grate | 4.20 | 20 | 15 | 12 | 9 | 7 | 3 | 0 |
| 3. | Continuous, Refractory, Traveling Grate | 20.87 | 31 | 27 | 24 | 21 | 15 | 10 | 3 |
| 4. | Continuous, Refractory, Grate & Kiln | 7.05 | 12 | 12 | 8 | 4 | 2 | 2 | 2 |
| 5. | Batch, Refractory, Circular | 24.30 | 2 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | Batch, Refractory, Rectangular Cell | 23.13 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7. | Batch, Refractory, Hearth | 13.15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8. | Continuous, Water Wall, Rocking Grate | 0.00 | 0 | 3 | 5 | 7 | 9 | 11 | 15 |
| 9. | Continuous, Water Wall, Reciprocating Grate | 0.00 | 2 | 2 | 2 | 4 | 5 | 5 | 7 |
| 10. | Continuous, Water Wall, Traveling Grate | 0.00 | 2 | 6 | 8 | 10 | 12 | 15 | 18 |
| 11. | Continuous, Water Wall, Suspension Burning | 0.00 | 2 | 5 | 6 | 3 | 3 | 4 | 5 |
| 12. | Continuous, Slagging Type I | 0.00 | 0 | 1 | 3 | 3 | 3 | 3 | 3 |
| 13. | Continuous, Slagging Type II | 0.00 | 0 | 2 | 6 | 10 | 14 | 17 | 18 |
| 14. | Continuous, Fluid Bed | 0.00 | 0 | 0 | 0 | 1 | 2 | 2 | 3 |
| 15. | Continuous, Pyrolysis | 0.00 | 0 | 3 | 8 | 13 | 18 | 21 | 25 |
| | | 100.00% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

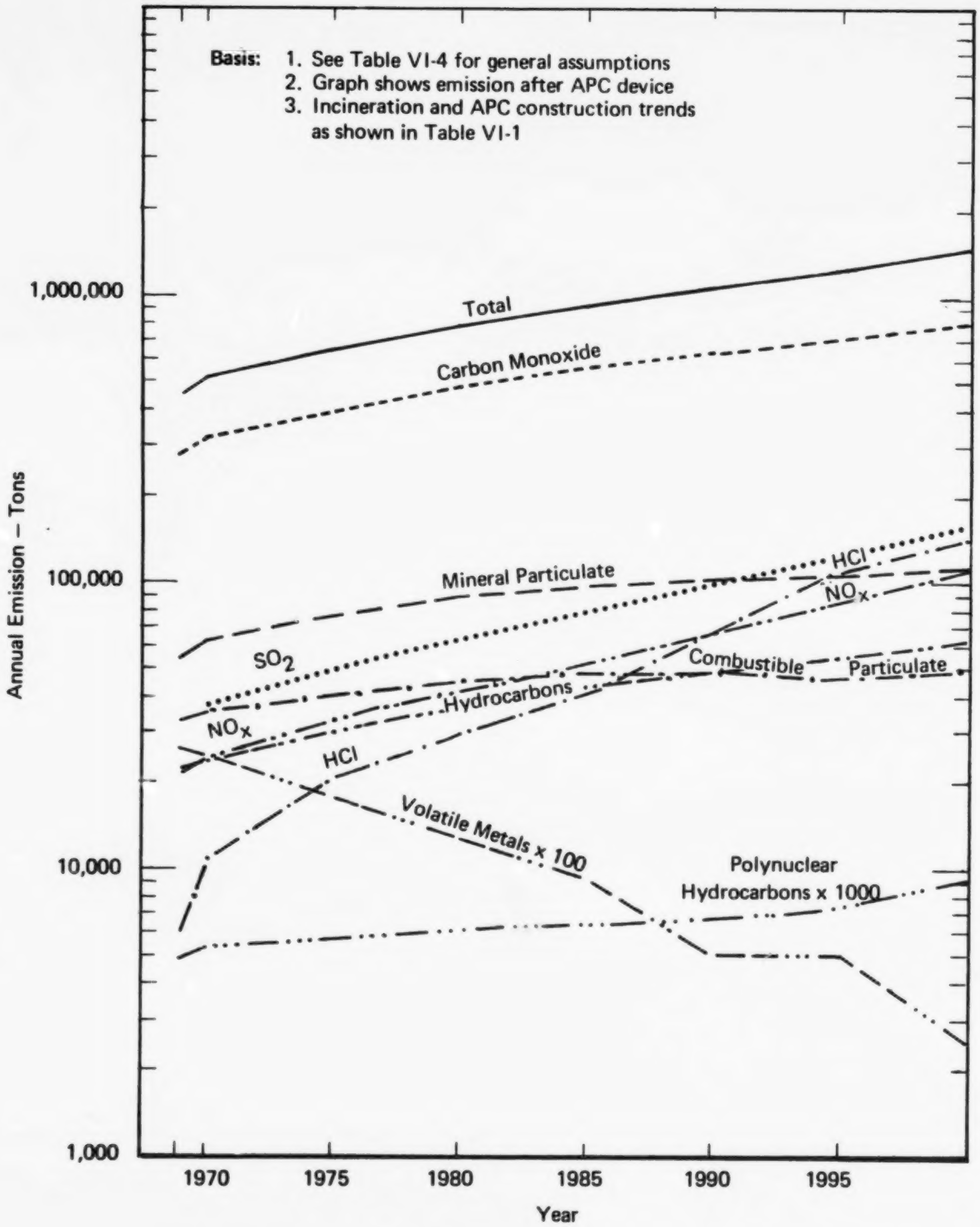
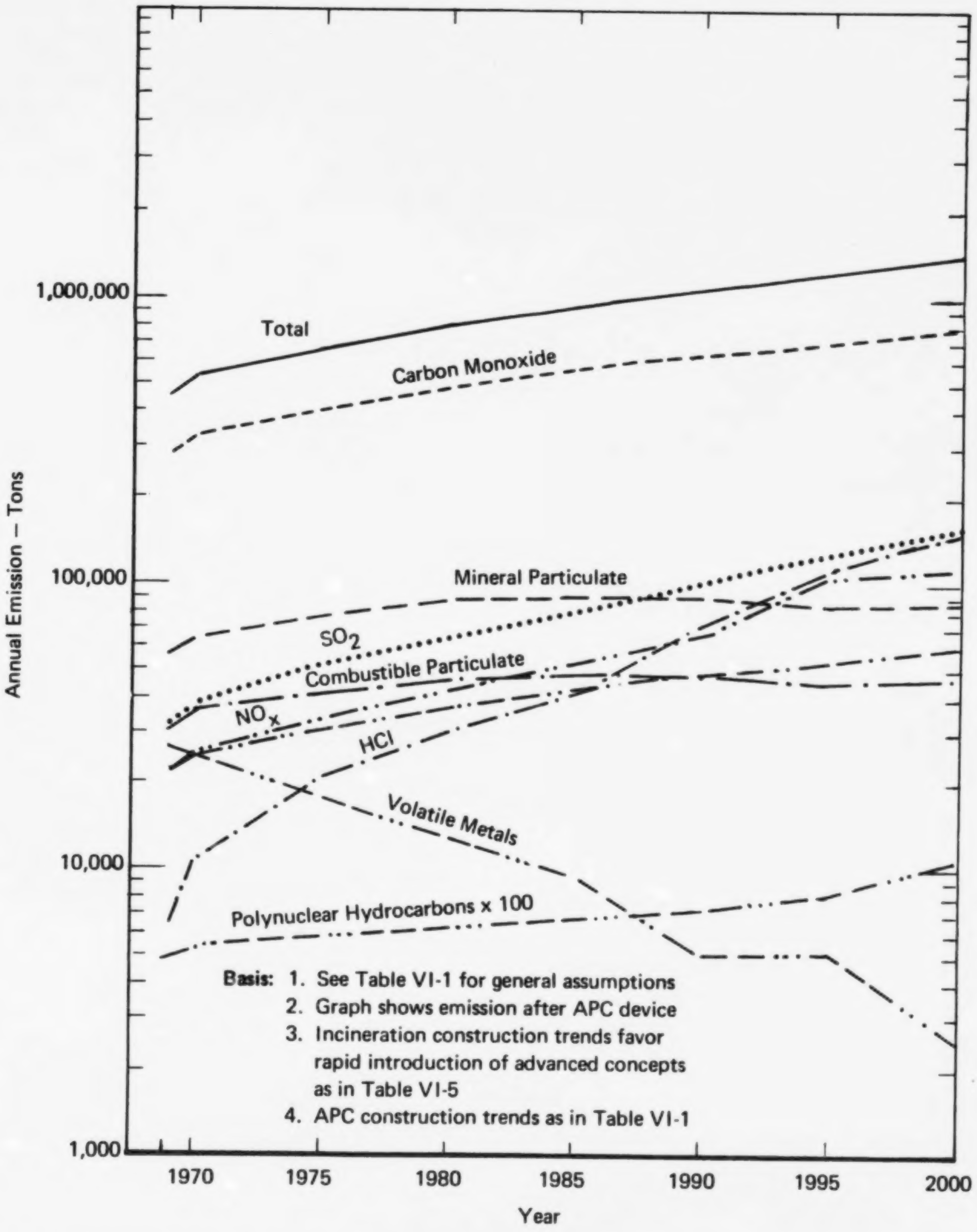
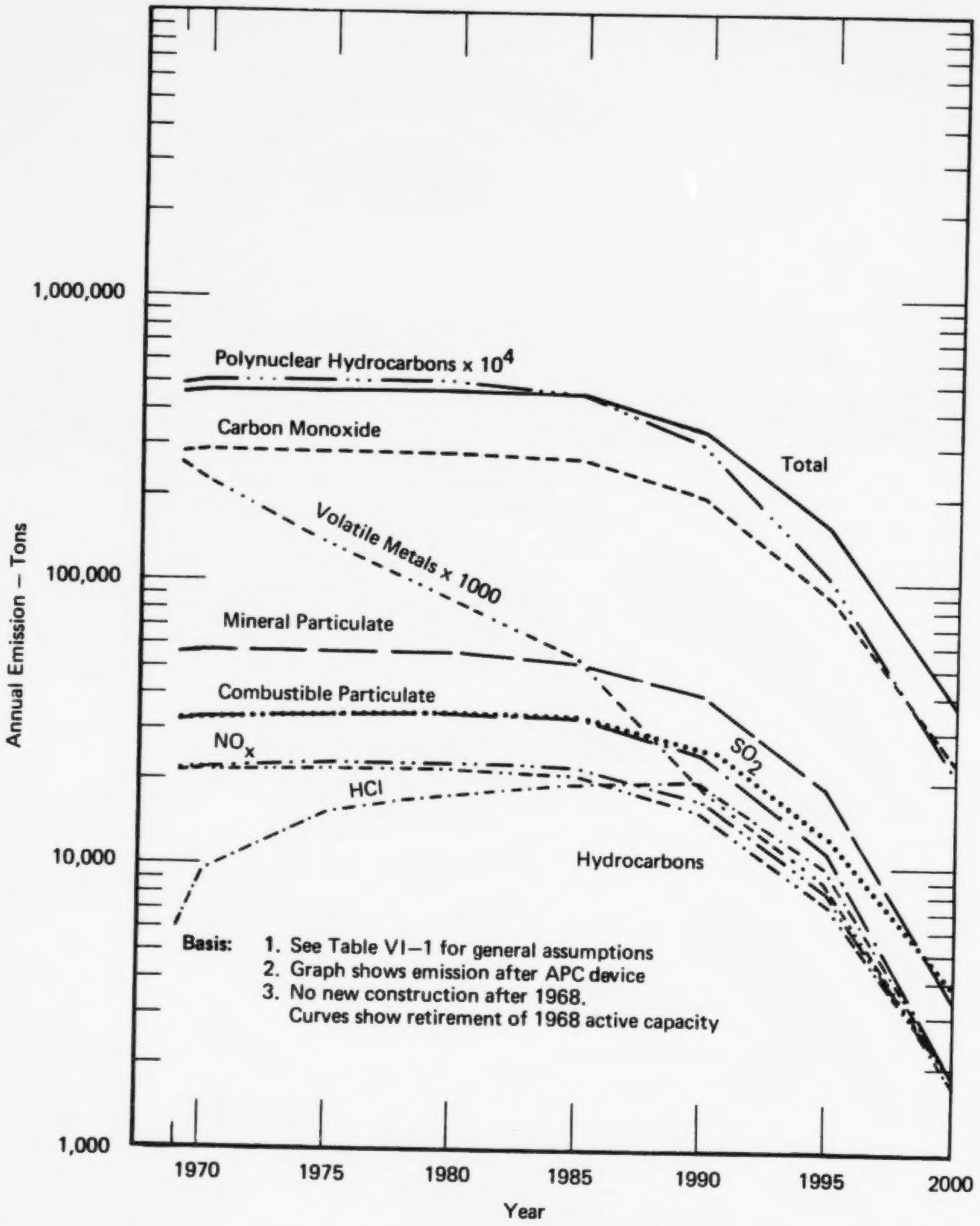


FIGURE VI–6 TOTAL ANNUAL STACK EMISSION ESTIMATES FOR U.S. MUNICIPAL INCINERATOR SYSTEMS



**Basis:** 1. See Table VI-1 for general assumptions
2. Graph shows emission after APC device
3. Incineration construction trends favor rapid introduction of advanced concepts as in Table VI-5
4. APC construction trends as in Table VI-1

FIGURE VI–7 TOTAL ANNUAL STACK EMISSION ESTIMATES FOR U.S. MUNICIPAL INCINERATOR SYSTEMS REFLECTING RAPID IMPLEMENTATION OF ADVANCED INCINERATION CONCEPTS



**Basis:**
1. See Table VI–1 for general assumptions
2. Graph shows emission after APC device
3. No new construction after 1968.
   Curves show retirement of 1968 active capacity

FIGURE VI–8 TOTAL STACK EMISSION ESTIMATES FOR EXISTING U.S. MUNICIPAL MUNICIPAL INCINERATOR SYSTEMS SHOWING POLLUTANT EMISSION DECLINE CAUSED BY PLANT RETIREMENT

evaluating the impact of alternative assumptions. Figure VI-8 may also be used to estimate the consequence of improved design or operating practices for existing plants in national emission rates.

Figures VI-9, 10 and 11 show the result of "national mineral particulate APC efficiency legislation" at various levels of control. For these calculations, all plants "built" after 1968 were equipped with APC systems of fixed efficiency. In Figure VI-9, the efficiency of all units installed after 1968 is that of the average APC particulate removal system efficiency of plants built in the 1963-1968 time period (approximately 52% for mineral particulates). In Figure VI-10, the APC efficiency is established at 70% and in Figure VI-11, the efficiency is established at 90%. The rapid increase in mineral particulate emission shown in Figure VI-9, in comparison to the other projections, shows the relatively low average efficiency of recent existing plants. It can be seen that the base projections for future incinerator APC efficiency are equivalent to somewhat greater than 70% and less than 90%.

From these calculations, it can be clearly seen that aggressive particulate air pollution codes can substantially reduce the emission levels. Even for a modest code (70%), the national particulate emission would be reduced 27% and 36% by 1990 and 2000, respectively, in comparison to the situation in which current APC selection practices (52% efficiency) are merely continued. Applying a 70% code to all existing plants (which have a mean particulate removal efficiency of only 38%) would substantially reduce incinerator-caused particulate pollution in the near term.

### 6. Projection Results – Economic Implications

As presented in the description of the projection model, capital investment and total operating costs (including fixed costs) were also calculated. Figure VI-12 indicates the net worth (1969 dollars), of the active installed incinerator capacity (excluding the APC system) as a function of time (the upper curve). Also shown for evaluation of the incremental cost per year is the incinerator decay curve which gives the declining value of plants built prior to 1968. It should be noted that, with a 35-year life, no "new" incinerators built at the direction of the model were retired within the projection period. Also, to the accuracy of the graph, the capital investment for implementation of advanced concepts falls on the reference base curve (i.e., no additional capital costs are incurred by introducing incineration concepts offering improved air pollution performance).

APC capital investment costs are shown separate from the incinerator investment in Figure VI-12. Since the incinerator portion of the total investment is constant for all alternatives in APC efficiencies, the incremental and total plant cost for various APC alternatives is thus made highly visible. For evaluation of the cost of new capacity, the APC decay curve for plants built prior to 1968 is shown.

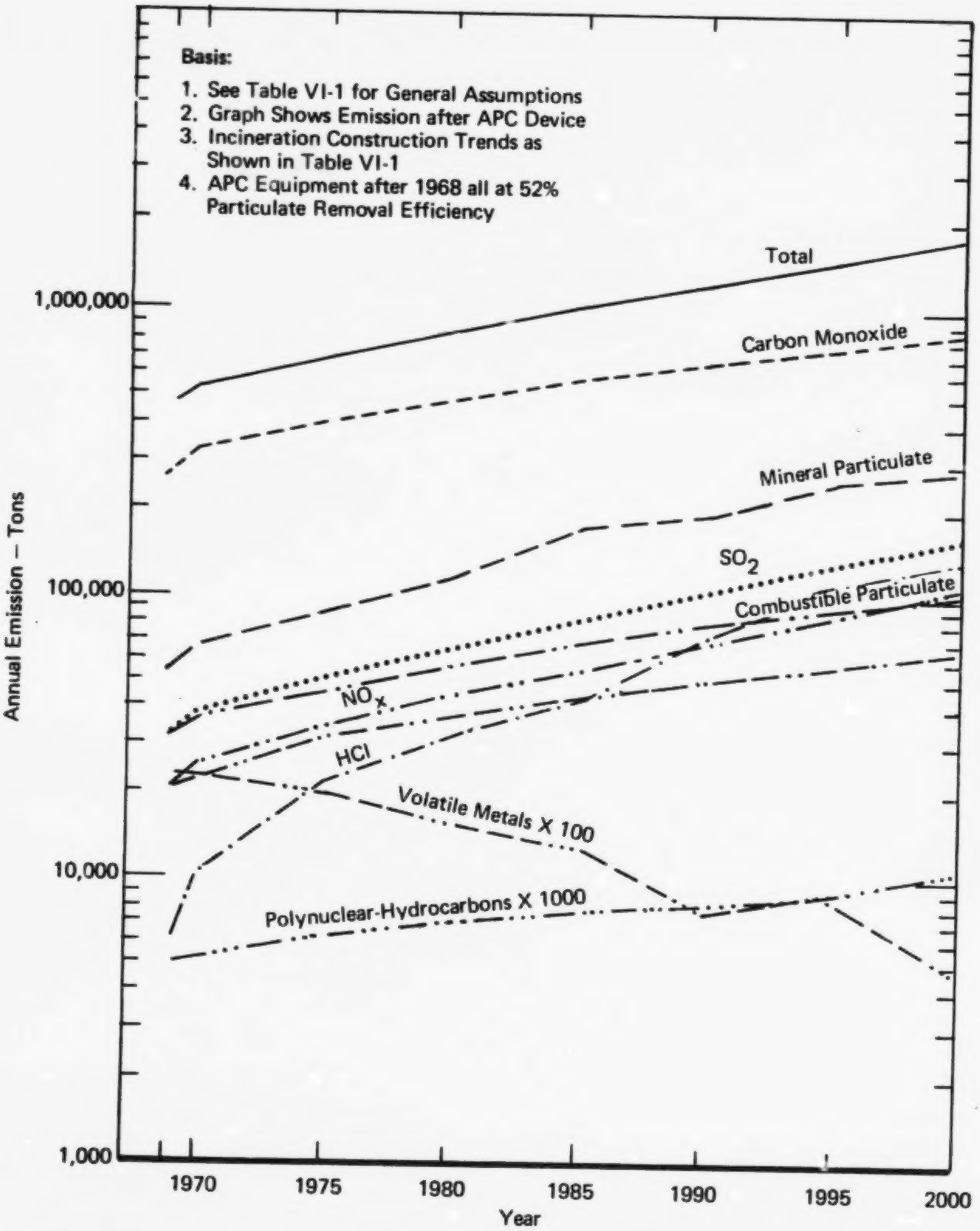
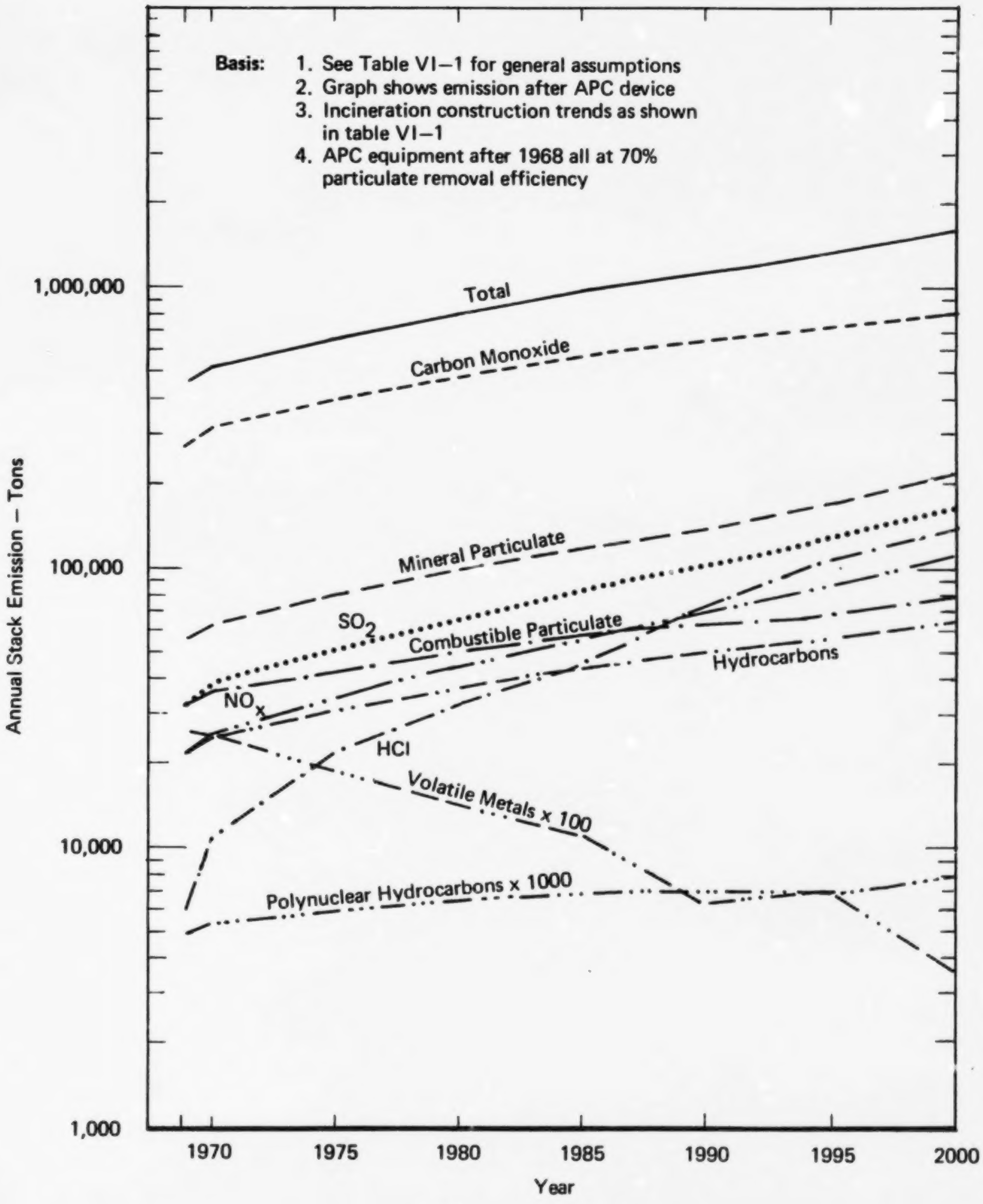


FIGURE VI–9 TOTAL ANNUAL STACK EMISSION ESTIMATES FOR U.S. INCINERATORS WITH POST-1968 PLANT APC PARTICULATE REMOVAL EFFICIENCY TYPICAL OF 1963 - 1968 INSTALLATIONS



**Basis:**
1. See Table VI–1 for general assumptions
2. Graph shows emission after APC device
3. Incineration construction trends as shown in table VI–1
4. APC equipment after 1968 all at 70% particulate removal efficiency

FIGURE VI–10 TOTAL STACK EMISSION ESTIMATES FOR U.S. MUNICIPAL INCINERATOR WITH POST-1968 PLANT APC PARTICULATE REMOVAL EFFICIENCY OF 70 %

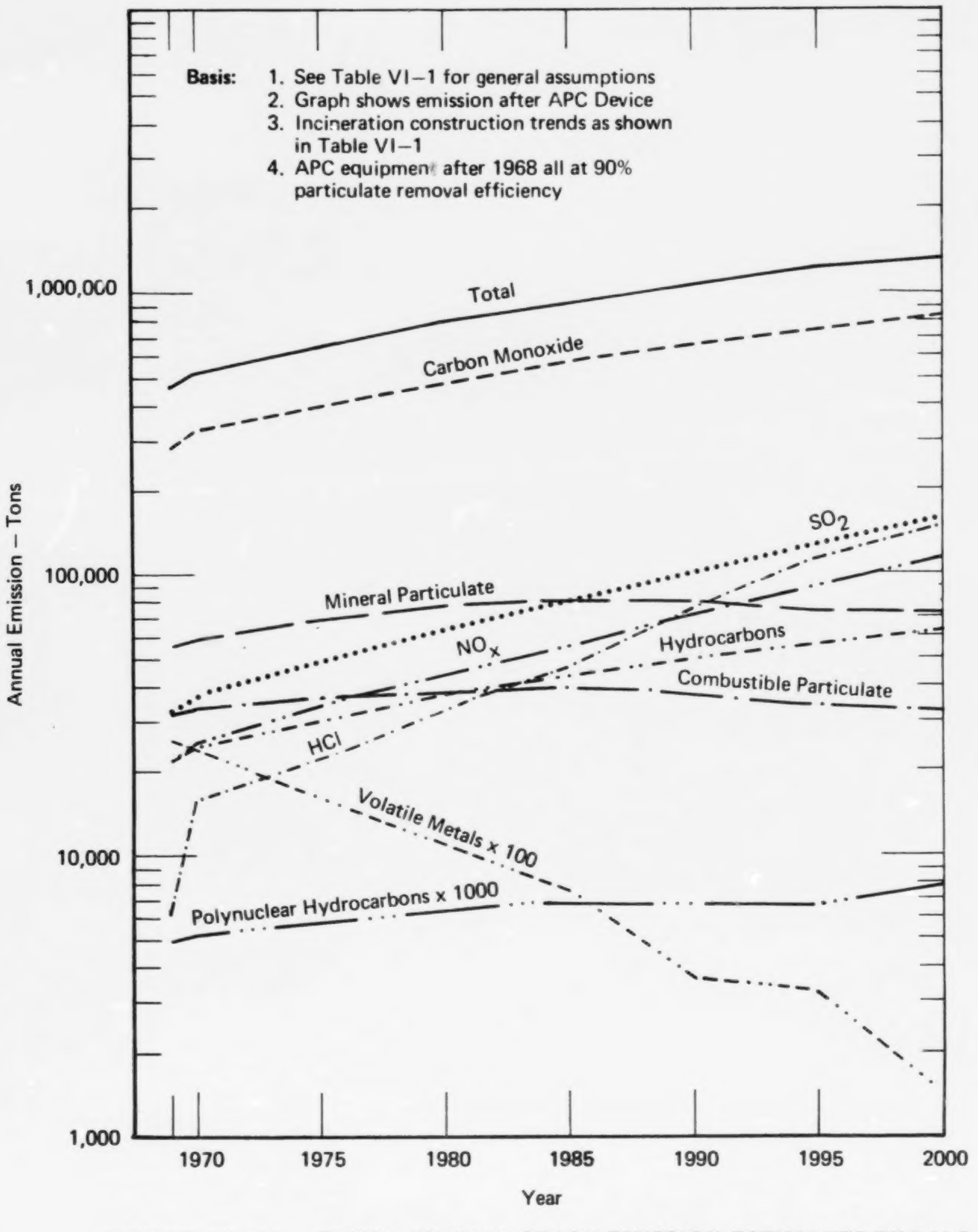
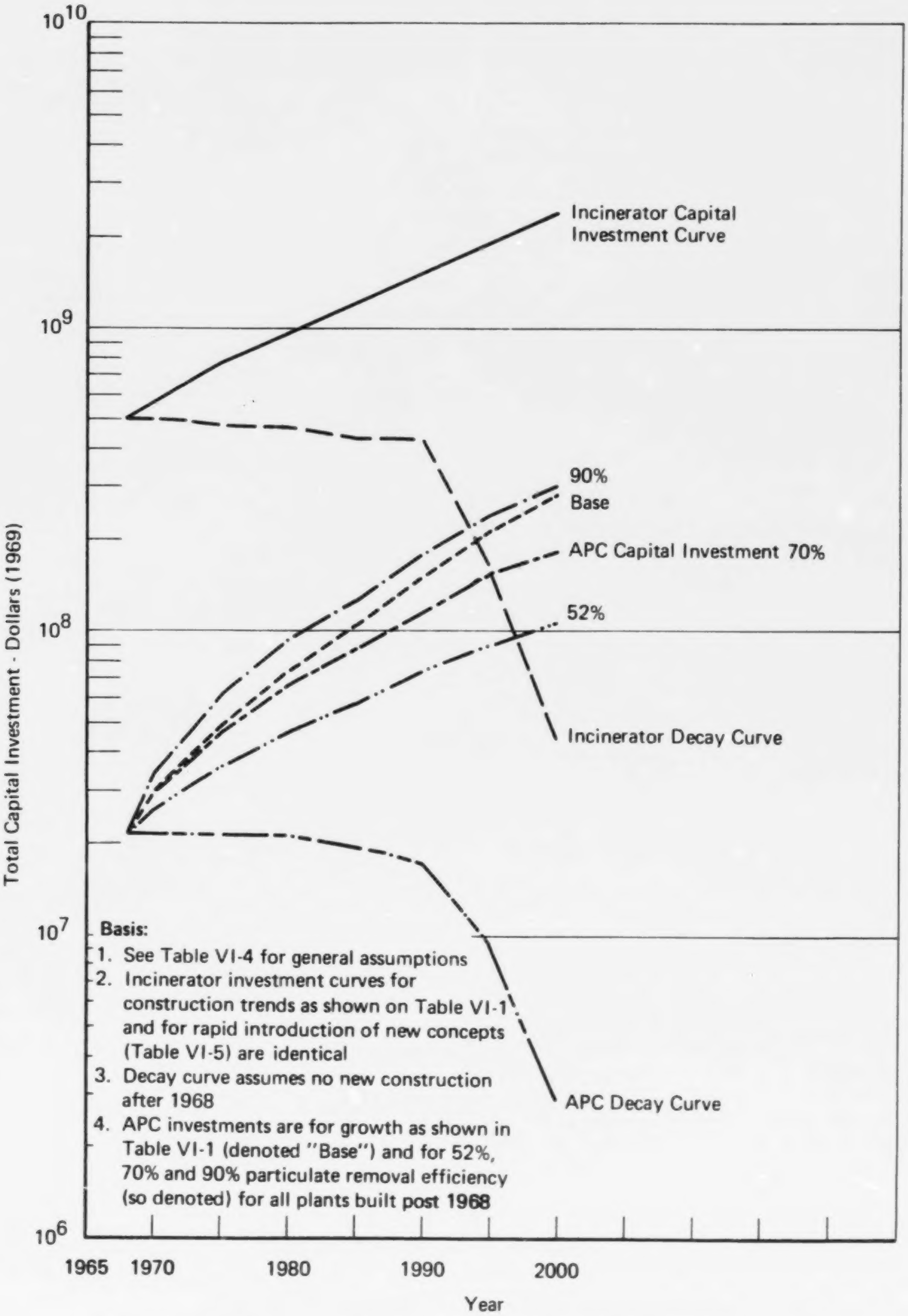


FIGURE VI–11 TOTAL ANNUAL STACK EMISSION ESTIMATES FOR U.S. MUNICIPAL INCINERATORS WITH POST-1968 PLANT APC PARTICULATE REMOVAL EFFICIENCY OF 90 %



**Basis:**

1. See Table VI-4 for general assumptions
2. Incinerator investment curves for construction trends as shown on Table VI-1 and for rapid introduction of new concepts (Table VI-5) are identical
3. Decay curve assumes no new construction after 1968
4. APC investments are for growth as shown in Table VI-1 (denoted "Base") and for 52%, 70% and 90% particulate removal efficiency (so denoted) for all plants built post 1968

**FIGURE VI–12** TOTAL ESTIMATED INVESTMENT VALUE OF ACTIVE U.S. MUNICIPAL INCINERATORS AND ASSOCIATED APC EQUIPMENT (1969 Dollars)

Figure VI-13 indicates the total incinerator operating costs, including interest and debt retirement, as developed by the model. As in the case of capital investment, the incinerator and APC operating costs are presented separately to indicate clearly the incremental costs at various levels of control. It is noteworthy that the rapid implementation of advanced concepts does not make a significant change in the total operating costs, but reference to Figure VI-7 shows a substantial drop in pollution emissions.

APC operation costs are seen to approximate 10% of the total operating costs. The projection results show, with reasonable sharpness, the relatively small cost of improved air pollution control relative to the *total* cost of incineration.

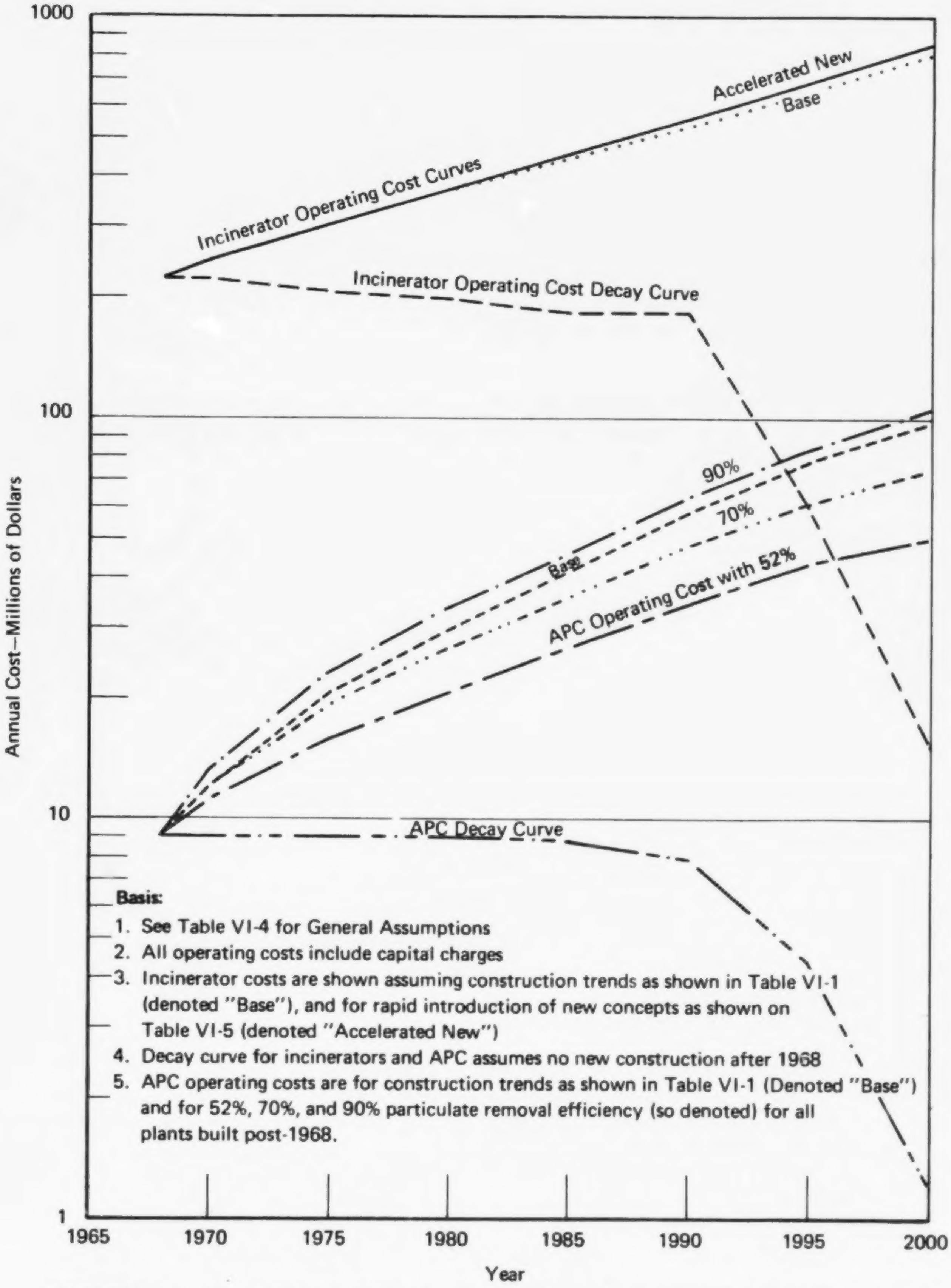
### 7. Projection Summary – Particulate and Combustible Pollutant Emissions

#### a. Particulate Emission

Figure VI-14 summarizes the total annual particulate stack emission rates for U.S. municipal incinerators at various levels of control. It is clearly visible that "modern practice" (the curve at 52% average control efficiency – equivalent to the average efficiency for plants built in 1963-1968) does not provide an acceptable guideline for the future. Indeed, if the urban air is to avoid further air quality degradation, existing plants must be upgraded and new plants built to far more exacting standards.

At a control level of 90% for all new plants, for example, the rapid increase in total emission can be essentially stopped; despite the anticipated four-fold increase in the quantity of refuse incinerated. Simultaneous improvements in effluent quality for existing plants could result in appearance of a minimum value in the total annual particulate emission rate between the present and the year 2000. It should be recognized, therefore, that to attain and sustain improved air quality, 90% control effectiveness is insufficient.

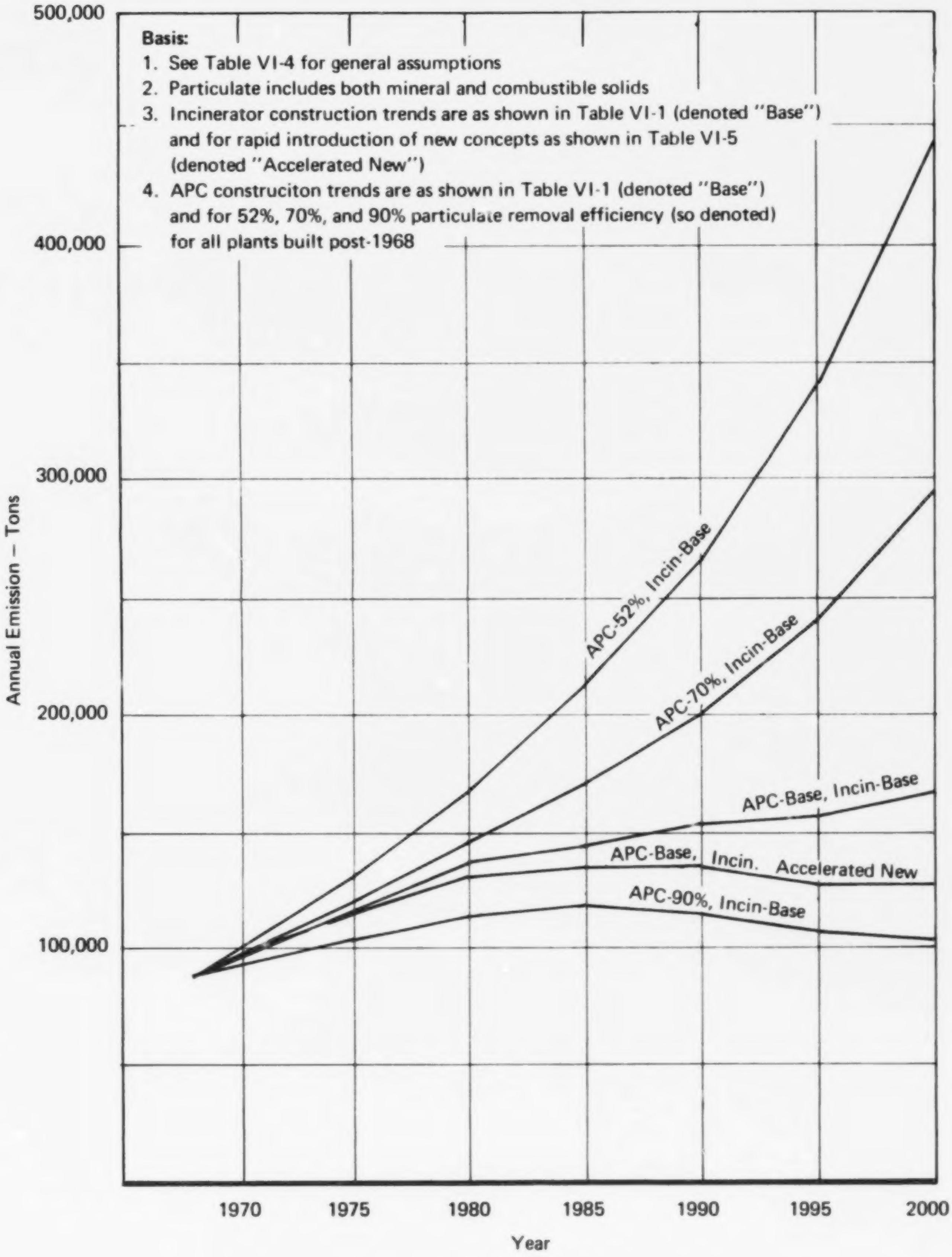
Also, further reductions in total particulate emission can be realized by improved combustion within existing and new incinerators. Because most of the combustible particulate is of small physical dimension (and thus difficult to collect), the fraction of combustible in the stack effluent increases as the overall particulate collection efficiency increases. The cost of collection systems to capture such fine particulates (most are below 5 microns in equivalent spherical diameter) is undoubtedly much higher than the cost for incinerator modification to improve combustion performance. This approach, therefore, opens the way to substantial reductions in the cost of a cleaner air environment.



**Basis:**

1. See Table VI-4 for General Assumptions
2. All operating costs include capital charges
3. Incinerator costs are shown assuming construction trends as shown in Table VI-1 (denoted "Base"), and for rapid introduction of new concepts as shown on Table VI-5 (denoted "Accelerated New")
4. Decay curve for incinerators and APC assumes no new construction after 1968
5. APC operating costs are for construction trends as shown in Table VI-1 (Denoted "Base") and for 52%, 70%, and 90% particulate removal efficiency (so denoted) for all plants built post-1968.

**FIGURE VI–13** TOTAL ESTIMATED ANNUAL OPERATING COST OF ACTIVE U.S. MUNICIPAL INCINERATORS AND ASSOCIATED APC EQUIPMENT (1969 Dollars), INCLUDING INTEREST AND DEBT RETIREMENT



**Basis:**

1. See Table VI-4 for general assumptions
2. Particulate includes both mineral and combustible solids
3. Incinerator construction trends are as shown in Table VI-1 (denoted "Base") and for rapid introduction of new concepts as shown in Table VI-5 (denoted "Accelerated New")
4. APC construciton trends are as shown in Table VI-1 (denoted "Base") and for 52%, 70%, and 90% particulate removal efficiency (so denoted) for all plants built post-1968

500,000
400,000
300,000
200,000
100,000
Annual Emission – Tons
APC-52%, Incin-Base
APC-70%, Incin-Base
APC-Base, Incin-Base
APC-Base, Incin. Accelerated New
APC-90%, Incin-Base
1970
1975
1980
1985
1990
1995
2000
Year

FIGURE VI–14 TOTAL ANNUAL PARTICULATE POLLUTANT STACK EMISSION ESTIMATES FOR U.S. MUNICIPAL INCINERATION – AT VARIOUS LEVELS OF CONTROL

b. Combustible Emission

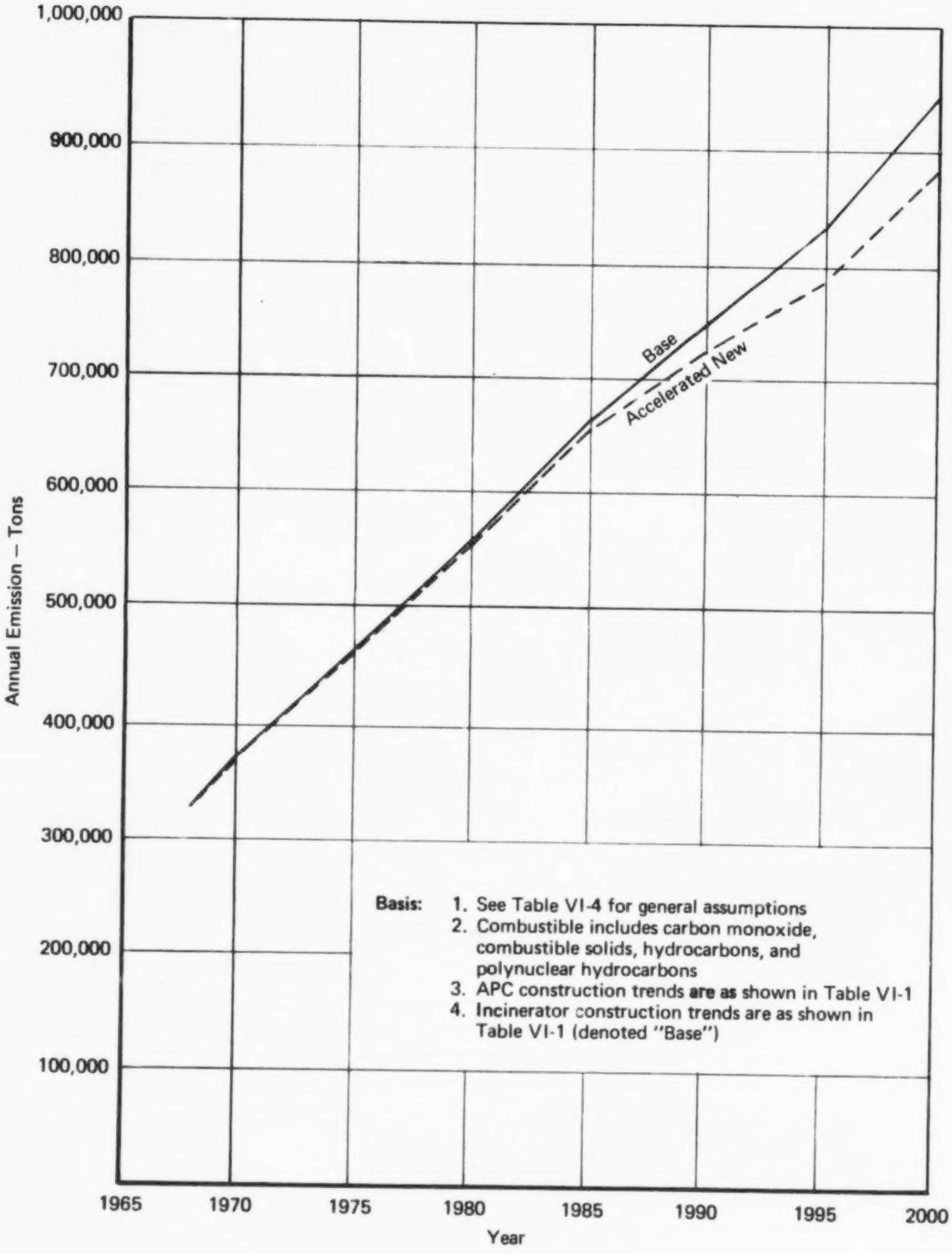
Figure VI-15 summarizes the total annual stack emissions of combustible pollutants. Based on continued use of "modern" incinerator combustion technology, the emission rate follows almost in parallel with the increases in refuse incineration. New concepts, with the exception of pyrolysis and fluid bed systems (which are primarily responsible for the slight improvement shown in Figure VI-15 for accelerated implementation of new techniques), do little to change this trend. Introduction of improved combustion concepts, however, could reduce these emissions by 25-75%. We feel that much of the basic technology for this improvement already exists. It is necessary, however, to demonstrate the validity of this assumption, recognizing that the special characteristics and constraints of refuse incinerator designs and operation may require new methods of application of this existing technology.

## C. REFERENCES

1. Technical-Economic Study of Solid Waste Disposal Needs and Practices
Combustion Engineering, Inc.
Vol. I – Conducted for the Bureau of Solid Waste Management
Contract PH-86-66-163, Nov. 1967.

2. Meeting the Challenge of Solid Waste Disposal
W. E. Gilbertson, R. J. Black, and K. Flieger
National Incinerator Conference, New York, 1966, pp. 49-53.

3. City and County Data Book, Bureau of the Census, 1967.



**Basis:**

1. See Table VI-4 for general assumptions
2. Combustible includes carbon monoxide, combustible solids, hydrocarbons, and polynuclear hydrocarbons
3. APC construction trends **are as** shown in Table VI-1
4. Incinerator construction trends are as shown in Table VI-1 (denoted "Base")

FIGURE VI–15 TOTAL ANNUAL COMBUSTIBLE EMISSION ESTIMATES FOR U.S. MUNICIPAL INCINERATION

# VII. TECHNICAL-ECONOMIC ANALYSIS OF THE AIR POLLUTION ASPECTS OF MUNICIPAL INCINERATION

# VII. TECHNICAL-ECONOMIC ANALYSIS OF THE AIR POLLUTION ASPECTS OF MUNICIPAL INCINERATION

## A. INTRODUCTION

The primary function of an incinerator plant is to reduce the volume economically and to sterilize solid waste. Most plants have been built and operated solely to meet this objective. Too often, incinerator air pollution control has been only a corrective action after the fact, sometimes applied to the plant effluent. In recent years, however, public outrage at the emission of air pollutants has resulted in the enactment of forceful air pollution codes, and has emphasized the plant performance objective of minimizing environmental pollution. Consequently, communities now operating incinerators are seeking ways to minimize emission; communities considering the installation of incinerator plants desire assurance that air pollution problems will not occur; and Federal, state, and municipal agencies supporting incinerator research are seeking new concepts which would promise a minimum of air pollution. This Chapter addresses these needs from both a technical and an economic standpoint.

The air pollutants arising from the incineration of solid wastes fall into three categories, probably at present in decreasing order of importance, at present:

- Mineral particulate;
- Combustible solids and gases; and
- Noncombustible gases.

It has been shown, in Chapter V, that the design and operating practices of a given plant have had little effect on the emission of mineral particulate, while the air pollution control (APC) system used has had a strong effect on emission. The emission of combustible solids and gases, on the contrary, is a strong function of design and operating practices but is affected little by the APC system used. Emission of noncombustible gaseous pollutants tends to be a weak function or independent of the design and operating practices. It is affected variably by the APC system, depending on the type, but it is a strong function of refuse composition.

As a result, the primary consideration in minimizing the emission of air pollutants from incinerators is the installation of appropriate air pollution control systems for the control of mineral particulate. The term "appropriate" is defined by the furnace effluent loadings observed or anticipated, the degree of control required, and local constraints, such as available space, pressure drop limitations, waste water disposal problems, preferences in the distribution of costs between investment and operating expenditures, etc.

Effective control of combustible pollutant emissions requires modification of the combustion chambers and/or improvements in operating practices, directed at minimizing their formation or maximizing their rate of destruction. Since these operating practice variations also affect the other criteria of incinerator performance (see Section D of Appendix H), consideration must be given to the overall implications of operating and design changes which are oriented toward the abatement of air pollution.

In this Chapter, the subject of air pollution control system effectiveness in the removal of particulate matter and gaseous pollutants is presented, followed by a summary discussion of APC system selection criteria, and investment and operating economics for each type. This is followed by a discussion of the modifications possible for existing plants (equipment additions or changes in operating practices) to minimize air pollution. This discussion is structured around the overall solid waste disposal Criteria of Performance (Section D of Appendix H). The third major section addresses the technology and economics of alternatives available for new incinerator plants, based on existing technology (although these concepts may not be used presently in incineration practice). Evaluations of incineration concepts now at a level of development requiring laboratory and/or pilot-scale demonstrations are then considered in the fourth major section, in the light of their potential economics and technical advantages and/or disadvantages.

## 1. Approach

### a. Air Pollution Control for Incinerators (Section B)

As discussed above, incinerator APC systems offer the most effective means to reduce emission of mineral particulate and are the only means of reducing the stack concentration of noncombustible, gaseous pollutants. The approach used in evaluation of APC system effectiveness for particulate matter was dictated by the limited removal efficiency data available. In most cases, emissions are measured only at the stack, to indicate compliance with local codes. Often, when particle loading measurements are made prior to the stack, several control systems are active (e.g., settling chamber followed by wet sprays and wet baffles) so that the effects of any one control concept are confused. Consequently, efficiencies of various types of APC systems are calculated from theory, and the results are compared with measured data. In general, there is fair agreement. Efficiency of removal of gaseous pollutants is also calculated from theoretical considerations. Almost no data is available for comparison with these results. However, with the exception of the halogen acids (for wet collectors), very low levels of control are anticipated.

The subject of APC systems selection is discussed from the standpoint of meeting local particulate emission standards. This summary discussion is followed by the presentation of approximate investment and operating costs for APC systems in incinerator service.

### b. Technical-Economic Analysis – Modifications to Existing Plants (Section C)

In considering modifications to existing plants (or for incinerators yet unbuilt), consideration must be given to meeting the Criteria of Performance described in Appendix H: reliability, safety, environmental pollution, cost, and the quality of residue. As is true of most complex systems, changing the design basis for one part of the plant or an important operating parameter to solve a given problem often affects other aspects of plant behavior. In order to assist in visualizing these interactions, the discussion of plant modifications to minimize air pollutant emission has been couched in the overall framework of these five plant performance objectives.

### c. Technical-Economic Analysis – Incineration Concepts Based on Existing Technology (Section D)

This portion of the report is addressed to the community seeking an incinerator which promises to meet, to the fullest extent possible, its "personalized" criteria of performance, which are weighted to reflect unique local needs. The discussion recognizes the diversity of needs from one community to another. There are often perspectives which are neither "right" nor "wrong," assuming that each community honestly and realistically evaluates its needs and responsibilities. Therefore, the discussion of the existing art is intended to provide a tool for decision-making rather than to preempt the decision-making process.

Meeting the criteria of safety and reliability requires only the application of good engineering design and practices. Particular problems with these two factors and methods to obtain acceptable residue quality are discussed in Section C (Modifications to Existing Plants). The subject of the design and operating characteristics of APC devices appropriate to minimize air pollution for these systems are discussed principally in Section B, following this introduction.

Plant economics (investment and total operating costs) are presented in detail in this section. In order to provide a consistent comparative basis, all economic evaluations were carried out with similar air pollution control systems (high-efficiency electrostatic precipitators) even if these are not the preferred type for the specific application. Section B, dealing with APC system applicability, provides the tools to modify plant economics for alternate APC systems.

d. Technical-Economic Analysis – Concepts Based on Advanced Technology (Section E)

Currently, a number of Federal, state, and municipal agencies, and private groups are seeking improved methods of solid waste incineration. In the case of incineration concepts based on existing technology (Section D), systems which adequately meet all of the Criteria of Performance are sought by these groups. The emphasis in this discussion is placed on presenting the state of technology and the technical potential of the concepts. Economics are treated only to the extent which is possible at the early stage in development. Many of the pertinent safety, reliability, residue quality and environmental pollution considerations applicable to these concepts are discussed in Section B (Air Pollution Control for Incinerators) and Section C (Modifications to Existing Plants).

## 2. Limitations

Throughout the technical-economic analysis, an attempt has been made to incorporate available data on emissions, costs, refuse characteristics, operating experience, etc., to produce results which have general validity. In any such distillation of information from sources of diverse but unknown reliability and variable basis, compromises and a measure of simplification is necessary. As a result, the description of plant configuration and problems is not specific, but generic; costs reflect national averages rather than budget estimates; and plant descriptions or refuse compositions do not form a basis for bid specifications. In any practical application, both assistance by competent engineering firms and appropriate data reflecting local realities are necessary for final decision-making.

The technical-economic analysis does not solve problems. Alternatives are described, however, with the associated system interactions and economics to provide the problem solver with the means and methodology to find solutions compatible with his unique needs. Absolute solutions do not exist.

## 3. Techniques for Use of Economic Data

In general, economic data are presented separately for capital investments and total operating cost. If appropriate, capital investments are given as a function of capacity (tons per 24-hr day, cubic feet per minute, etc.). In all cases, the capital investments are on the common basis of construction and equipment costs for Boston, Massachusetts, in 1969 dollars. Operating cost, in all but the few cases where it is specifically contraindicated, *includes* debt retirement (amortization) and interest charges.

The reference base for all cost estimates is presented in Table VII-1. It is recognized that throughout the country, many differences exist between the reference base used in this report and local conditions. As a result, a simplified technique is provided to allow the reader to adjust investment and operating costs to correspond with local realities.

For all major investment and operating cost evaluations, an operating cost distribution table is provided. An example of this is shown in Table VII-2 where the distribution of cost for "Equipment Type XXX" is presented. In the example shown, it is seen that plant usage (operating hours per year) is an important variable and, as a result, the cost distributions are given for two operating schedules. In some actual cases throughout the text, the effects of capacity must also be included, yielding an even more comprehensive table. In association with the cost distribution table would be a graphical presentation of operating costs versus some extensive parameter, such as equipment capacity.

Table VII-3 shows a sample calculation to illustrate the method by which cost estimates presented in this report may be localized, in areas of the country other than Boston, Massachusetts, and to times different from the reference point of mid-1969. Because of the rather wide differences in labor rates, capital charges and utility costs throughout the country, it will most likely be necessary for those wishing to use the results of the analysis to make these modifications. Such modifications must be made for each system, however, as the distribution of costs among the major cost centers is variable.

### 4. Concept Presentation Format

In discussing alternative incineration concepts, the following organization has been used for uniformity and clarity:

- Process Description
- Advantages
- Disadvantages
- Problem Areas

The "Process Description" portion of each presentation, as the name implies, is a description of the unique features of the concept. Where appropriate, several similar concepts are preceded by a generalized introduction, where the common characteristics are discussed collectively.

# TABLE VII-1

## REFERENCE BASE FOR COST ESTIMATES

The following cost basis was used for all calculations of operating costs:

A. **Capital**

1. Amortization - Straight Line
   - a. Process equipment - 15 years (6.67%/yr)
   - b. Buildings and foundations - 20 years (5%/yr)
2. Debt Interest

   20 year, 6% municipal bonds, incurring an average annual charge of 3.00%/yr on the initial total investment.
3. Insurance - none (assumed self-insured)

B. **Operating Labor**

1. Salaries and Wages
   - a. Supervisors - $14,000/yr
   - b. Skilled labor - $5.00/hr
   - c. Unskilled labor - $3.00/hr
2. Overhead (applied to all labor charges)

| | | |
|---|---|---|
| a. | Fringe Benefits | 35% |
| b. | General and Administrative | 5% |
| | | 40% |

C. **Utilities**

1. Water - 30¢/1000 gal
2. Boiler Water Treatment - 4¢/1000-lb steam
3. Electricity - 1.5¢/kw-hr
4. Natural Gas - 80¢/1,000,000 Btu

D. **Location and Time Reference**[17]

1. Boston, 1969
2. Engineering News Record Indexes

   a. Common Construction Labor: 170
   b. Skilled Construction Labor: 167
   c. Construction Equipment Operators: 187
   d. Construction Cost Index: 1202
   e. Building Cost Index: 801

E. **Reference Engineering News Record Indexes - Construction Cost Index for 1969**[17]

| | |
|---|---|
| Atlanta | 962 |
| Baltimore | 1006 |
| Birmingham | 961 |
| Boston | 1202 |
| Chicago | 1412 |
| Cincinnati | 1455 |
| Cleveland | 1629 |
| Dallas | 1001 |
| Denver | 1108 |
| Detroit | 1513 |
| Kansas City | 1172 |
| Los Angeles | 1331 |
| Minneapolis | 1313 |
| New Orleans | 1027 |
| New York | 1601 |
| Philadelphia | 1239 |
| Pittsburgh | 1379 |
| St. Louis | 1498 |
| San Francisco | 1475 |
| Seattle | 1413 |
| Montreal | 1152 |
| Toronto | 1071 |
| U. S. Average | 1270 |

## TABLE VII-2

## SAMPLE OPERATING COST DISTRIBUTION (PERCENT)
## EQUIPMENT TYPE XXX

| Operating Schedule | 2000 hr/yr (1 shift) | 6000 hr/yr (3 shifts) |
|---|---|---|
| Capital Charges | 50% | 20% |
| Labor | 20 | 35 |
| Water | 10 | 10 |
| Electricity | 20 | 35 |
|  | 100% | 100% |

The second portion of each process presentation is concerned with the advantages of the system. As used in this report, "Advantages" refer to aspects which are *inherently attractive* of the system. Process "Disadvantages," on the contrary, are those aspects which are *inherently unhelpful*. For example, if batch feeding is undesirable, this is an inherent disadvantage of any batch-fed system. "Problem Areas" are those characteristics of the system, as it is presently used or understood, which appear *tractable* to engineering research and development. Continuing with the example of batch-feeding, if the influx of cold air when the charging gate is opened is a major problem in batch-fed systems, an air-lock feed system which prohibits this can readily correct the situation. Thus, for the purpose of this report, the influx of air on charging is not a disadvantage but rather a problem area which can be dealt with in the modification of existing plants or in the design of future plants. In some cases, problem areas simply reflect unfavorable design features which can often be corrected by the substitution of alternative equipment. In other cases, eliminating problem areas will require research and testing, but it is felt that "breakthroughs" are not required.

## B. AIR POLLUTION CONTROL FOR INCINERATORS

### 1. Introduction

Air pollution is an important measure of the quality of life in the urban environment. As the public demands for clean air grow, increased attention has been given to the incineration of refuse as a source of pollution. Although incineration only contributes a few percent of the total national air pollution load, the economics of refuse transportation and other issues have placed these sources near the heart of the cities. In addition, the black flakes of particulate emitted from many of the older plants are visible and highly objectionable to the city dwellers. As a consequence of the public outcry, increasing numbers of municipal governments are evaluating the air pollution performance of existing plants and seeking new and improved standards of performance for plants still in the planning stage. It is the purpose of this portion of the report to provide the technical and economic data necessary for preliminary decision-making in this area.

## TABLE VII-3

## SAMPLE CALCULATION – LOCALIZATION OF ANNUAL OPERATING COST ESTIMATES

1. Assume that the cost basis is as follows:

| Item | Basis in Report and Table VII-1 | Local Costs |
|---|---|---|
| Capital | 8% | 10% |
| Average Total Labor (inc. overhead) | \$30/hr | \$20/hr |
| Water | 30¢/M gal | 5¢/M gal |
| Electricity | 1.5¢/kw hr | 1.5¢/kw hr |

2. Prepare a multiplier table as follows:

Cost Item Multiplier = Local Average/Report Basis

Capital: 10/8 = 1.25
Labor: 20/30 = 0.67
Water: 5/30 = 0.17
Elect.: 1.5/1.5 = 1.00

3. Referring to the sample cost distribution in Table VII-2, for 2000 hr/yr (1 shift) operation, perform the following calculations:

| Item | % of Cost (Table VII-2) | | Multiplier | | Factor |
|---|---|---|---|---|---|
| Capital | 50% | x | 1.25 | = | 62.5% |
| Labor | 20 | x | 0.67 | = | 13.4 |
| Water | 10 | x | 0.17 | = | 1.7 |
| Electricity | | | | | |

Capital: 10/8 = 1.25
Labor: 20/30 = 0.67
Water: 5/30 = 0.17
Elect.: 1.5/1.5 = 1.00

3. Referring to the sample cost distribution in Table VII-2, for 2000 hr/yr (1 shift) operation, perform the following calculations:

| Item | % of Cost (Table VII-2) | | Multiplier | | | Factor |
|---|---|---|---|---|---|---|
| Capital | 50% | x | 1.25 | = | | 62.5% |
| Labor | 20 | x | 0.67 | = | | 13.4 |
| Water | 10 | x | 0.17 | = | | 1.7 |
| Electricity | 20 | x | 1.00 | = | | 20.0 |
| | | | | | Total | 97.6% |

A similar calculation for a 6000-hr/yr (3 shift) operation yields a factor of 85.1%.

4. The local total operating costs can then be computed from cost data shown in the report (usually presented as a graph), by taking 97.6% and 85.1% of the values shown for one-and three-shift operations, respectively. For example, the total operating cost for Equipment Type XXX would be computed as follows:

| Operating Schedule | Total Operating Cost ($/ton, $/yr. etc.) From Cost Curve in Report | | Factor (Expressed as Decimal) | | Local Cost |
|---|---|---|---|---|---|
| 1 shift | $16.00 | x | 0.976 | = | $15.62 |
| 3 shifts | $12.00 | x | 0.851 | = | $10.21 |

5. If the plant were to be located where construction costs differ from those in Boston, or at some time in the future when costs are higher, say, Cincinnati, review of the Engineering News Record Construction Cost Index could establish a local value of, say, 1560 (in comparison to the 1969 Boston reference of 1202). In this case, the Capital multiplier developed in 3. above, should be calculated as follows:

$$\begin{aligned}\text{Capital Multiplier} &= \left(\frac{\text{Local Average}}{\text{Report Basis}}\right) \left(\frac{\text{Local ENR Index}}{\text{Boston Reference (Table VII-1)}}\right)\\ &= \left(10/8\right) \left(\frac{1560}{1202}\right)\\ &= 1.62\end{aligned}$$

Continuing as in 3. above, one gets new overall factors of 116.2% and 92.6% for 1 and 3 shifts respectively. These new factors are then used as in 4. to compute the current load cost.

B

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Pollution control for incinerators is essentially particulate control. Substantial technology exists to control this pollutant; and, indeed, satisfactory abatement efficiencies exceeding the most stringent proposed emission standards are well within the capabilities of the existing art. Each city, however, has unique needs reflecting the background pollution from other sources, the location of the plant, and natural dissipative factors, such as strong winds or seaside location. Thus, objective comparative data is necessary in order to allow selection of equipment in line with specific needs.

The paragraphs which follow discuss the anticipated performance and cost of conventional air pollution control equipment for application to municipal incineration. Incinerator particulate exhibits unique characteristics of particle-size distribution, particle shape, and physical and electrical properties. Therefore, the performance of APC equipment in incinerator service can be expected to be different from coal boiler fly ash, steel plant fumes, etc. Based on limited existing data on the concentration and properties of incinerator fly ash and other pollutants, APC removal efficiency can be computed from theory and compared with measured efficiencies. The discrepancies which appear in such a comparison reflect uncertainties in the nature of the flue gas pollutants for the tests, ignorance of the precise nature of incinerator fly ash (spheres, plates, needles, etc.), and difficulties in analyzing the processes and flows within air pollution control equipment.

Selection of a particular type of air pollution control device represents a compromise between the initial capital investment required, the annual operating cost, and the collection efficiency. In addition, less definable parameters relating to operating characteristics, reliability, and water pollution potential, etc., must be considered. In order to clearly show the relative costs of APC systems, a comprehensive analysis is needed. Although a number of such evaluations are available, basic assumptions in many cases are hidden within lump-sum numbers, and the sensitivity of the results to those assumptions is not visible. We have attempted to avoid this problem in the following presentations.

### 2. Method of Analysis

Section D deals with the anticipated performance and cost of conventional air pollution control equipment when applied to municipal incinerators. First, a nominal composition and particle-size distribution was assumed for incinerator effluents based on a thorough review of published literature. Then, the types of available equipment and their predicted performance with this inlet stream were evaluated. The predicted performance was compared, where possible, with observed data, and the major reasons for discrepancies were analyzed. In general, the chief cause of uncertainty in the prediction of the performance of low pressure drop devices (settling chambers, baffles, cyclones) is the effect of individual designs on turbulence within the devices with subsequent reentrainment of trapped particles. An additional cause of error in predicting the performance of the higher-efficiency device is the paucity of data on particle-size distribution, particularly in the range below 2 microns, where no practical standard field methods of analysis exist.

Cost information, on both investment and operations, was collected or developed for each of the systems considered. These data were then integrated with the performance evaluation results to depict cost-effectiveness relationships.

### 3. Nominal Furnace Effluent Composition

In order to evaluate the performance of air pollution control systems for the removal of particulate and gaseous species, a nominal furnace effluent composition must be established. The description of effluent characteristics must include particle-size distributions and approximate concentrations of gaseous species. This reference point then provides a basis for comparison which reflects the variability of performance of APC systems having characteristics and concentration attributable to pollutants.

Although such a reference composition is a useful tool for APC evaluation, it must be recognized that differences in refuse composition, incinerator design, and operating practices cause variations in particulate quantity and size distributions and variations in the concentrations of gaseous species. With other influent characteristics, the performance of various APC systems will shift, although it is unlikely that marked performance changes will occur.

#### a. Particulate

A thorough search of the literature has disclosed no reliable data, except those of Walker and Schmitz,[1]* concerning particle-size distribution of domestic incinerator dust as it issues from the furnace. Their data are presented in Table VII-4. The three particle-size distributions determined during this research are plotted in Figure VII-1; for comparison, a curve depicting European experience according to Andritzky[2] is included. Other data on particle-size distribution for collected ash and for stack effluent ash (after the APC device) are shown in Table VII-5. As expected, the mass average particle diameter for emitted ash is consistently smaller than the collected ash.

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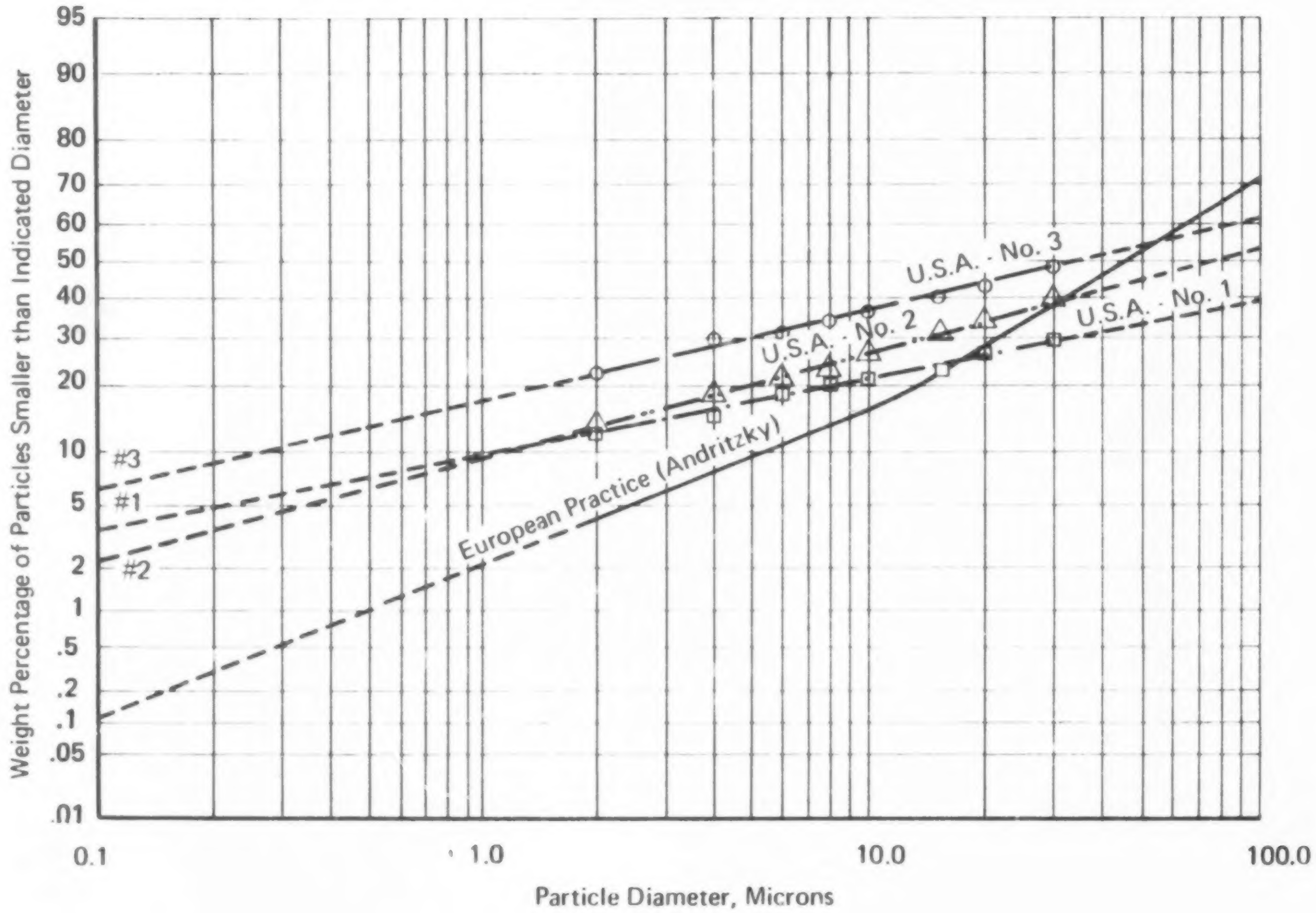
*All superscript numbers are keyed to the list of references at the end of this chapter.

## TABLE VII-4

## SUMMARY OF WALKER AND SCHMITZ FURNACE EMISSION DATA[1]

| **Installation:** | U.S.A. No. 1<br>**250 TPD**<br>**Continuous**<br>**Multiple**<br>**Traveling Grate** | U.S.A. No. 2<br>**250 TPD**<br>**Continuous**<br>**Reciprocating**<br>**Grate** | U.S.A. No. 3<br>**120 TPD**<br>**Continuous**<br>**Rocking**<br>**Grate** |
|---|---|---|---|
| Refuse Rate during Test, tons/hr | 12.9 | 9.8 | 5.1 |
| Underfire Air, SCFM/ft$^2$ grate | 41.8 | 105.0 | 17.5 |
| Outlet Temperature, °F | 1469.0 | 1211.0 | 1593.0 |
| $H_2O$ Content, % (vol) | 7.8 | 4.4 | 8.7 |
| $CO_2$ Content, % (vol) | 6.0 | 5.0 | 7.0 |
| $O_2$ Content % (vol) | 13.7 | 13.8 | 13.3 |
| Particulate Emission, lb/hr | 156.0 | 241.0 | 46.1 |
| Particulate Loading, grains/SDCF | 0.553 | 0.694 | 0.380 |
| Size Analysis (Bahco) | | | |
| Wt. % below 2 microns | 13.5 | 14.6 | 23.5 |
| Wt. % below 4 microns | 16.0 | 19.2 | 30.0 |
| Wt. % below 6 microns | 19.0 | 22.3 | 33.7 |
| Wt. % below 8 microns | 21.0 | 24.8 | 36.3 |
| Wt. % below 10 microns | 23.0 | 26.8 | 38.1 |
| Wt. % below 15 microns | 25.0 | 31.1 | 42.1 |
| Wt. % below 20 microns | 27.5 | 34.6 | 45.0 |
| Wt % below 30 microns | 30.0 | 40.4 | 50.0 |



**Sources:** European: Andritzky, M., Brennstoff-Wärme-Kraft *19*(9), 436(1967)
U.S.A.: Walker, A B and Schmitz, FW, Proc. 1966 ASME Nat'l. Incin. Conf., pp 64-73

FIGURE VII–1 PARTICLE SIZE DISTRIBUTIONS OF FURNACE EFFLUENTS

TABLE VII-5

## INCINERATOR EFFLUENT PARTICLE-SIZE

| Plant No.[a] or (Ref. No.) | Furnace Capacity TPD | Year Built | APC Type | Grate Type | Sample Point | Remarks | 1 µ | 2 µ | 4 µ |
|---|---|---|---|---|---|---|---|---|---|
| (1) | 250 | – | dry expan | 2 trav. | furnace | OF | 10 | 13.5 | 16.0 |
| (1) | 120 | – | wet wall | rocking | furnace | UF and OF | 17 | 23.5 | 30.0 |
| (1) | 250 | – | wet baff. | recip. | furnace | UF | 10 | 14.6 | 19.2 |
| (40) | | | | | furnace | range | 3-4 | 6.5-<br>10.5 | 12-<br>21 |
| (2) | | | | | furnace | | 2.3 | 4.5 | 8 |
| (17) | 220 | – | mech. cyclone | 2 trav. | after cooling bef APC | UF and OF | 2.5 | 7 | 18 |
| 4 | 250 | 58 | dry cyclone | circular | coll'td. | UF and OF | | | |
| 18 | 250 | 61 | wet wall | 2 trav. | coll'td. | | 0.6 | 2.8 | 7.2 |
| 89 | 240 | – | E. Pptr. | barrel | coll'td. | IH Europe | 0.2 | 1.8 | 6.5 |
| | | | E. Pptr. | | coll'td. | OH Europe | 0.05 | 3.0 | 9.0 |
| 87 | 267 | 66 | E. Pptr. | rocking | coll'td. | IH Europe | 0.5 | 4.0 | 10.7 |
| | | | E. Pptr. | | coll'td. | OH Europe | 0.01 | 0.2 | 1.2 |
| 88 | 500 | 64 | E. Pptr. | recip. | coll'td. | IH Europe[b] | 1.6 | 3 | 4 |
| | | | E. Pptr. | | coll'td. | OH Europe[b] | 0.25 | 1.2 | 3 |
| 94 | 250 | 66 | E. Pptr. | 5 trav. | coll'td. | European | 1 | 3.4 | 7.6 |
| (41) | | | dry expan | | emitted | typical | 1.1 | 3.3 | 10.0 |
| 20 | 250 | 62 | wet baff | 2 trav. | emitted | at 122.6% cap., OF | | | 1.2 |
| | | | | | emitted | at 122.6% cap., OF | | | 0.3 |
| | | | | | emitted | at 120.0% cap., OF | | | 0.65 |
| (42) | 250 | 53 | wet wall | 2 trav. | emitted | | | | 8 |
| (44) | 250 | 61 | spray | 2 trav. | emitted | UF and OF | | | 3.5 |
| | 250 | 61 | spray | 2 trav. | emitted | UF and OF | | | 1.7 |
| | 250 | 53 | wet wall | 2 trav. | emitted | | | | 10.7 |
| 1 | 250 | 67 | wet wall | 3 trav. | emitted | UF and OF | 0.5 | 2.3 | 4.2 |
| 17 | 250 | 53 | wet wall | 2 trav. | emitted | (data in question) | | | |
| 14 | 250 | 61 | wet baff | 2 trav. | emitted | UF and OF | | 2.3 | 10.0 |
| (43) | 300 | 55 | scrubber | rocking | emitted | UF and OF | | | |
| (42) | 250 | 54 | dry expan | 2 trav. | emitted | UF and OF | | | |

**Keys and Notes:**

IH - Hopper on inlet side of precipitator
OH - Hopper on outlet side of precipitator
OF - Overfire air in use
UF - Underfire air in use

[a] Plant Numbers refer to Incinerator Data in Table J-1, Appendix J. References (numbers in parentheses) may be found in Section F, Chapter VII.

[b] Coal being fired in furnace - with common flue

TABLE VII-5

INCINERATOR EFFLUENT PARTICLE-SIZE DISTR

| Plant No.[a] or (Ref. No.) | Furnace Capacity TPD | Year Built | APC Type | Grate Type | Sample Point | Remarks | 1 µ | 2 µ | 4 µ | 6 µ |
|---|---|---|---|---|---|---|---|---|---|---|
| (1) | 250 | – | dry expan | 2 trav. | furnace | OF | 10 | 13.5 | 16.0 | 19.0 |
| (1) | 120 | – | wet wall | rocking | furnace | UF and OF | 17 | 23.5 | 30.0 | 33.7 |
| (1) | 250 | – | wet baff. | recip. | furnace | UF | 10 | 14.6 | 19.2 | 22.3 |
| (40) | | | | | furnace | range | 3-4 | 6.5-10.5 | 12-21 | 17-29 |
| (2) | | | | | furnace | | 2.3 | 4.5 | 8 | 12 |
| (17) | 220 | – | mech. cyclone | 2 trav. | after cooling bef APC | UF and OF | 2.5 | 7 | 18 | 25 |
| 4 | 250 | 58 | dry cyclone | circular | coll'td. | UF and OF | | | | |
| 16 | 250 | 61 | wet wall | 2 trav. | coll'td. | | 0.6 | 2.8 | 7.2 | 8 |
| 89 | 240 | – | E. Pptr. | barrel | coll'td. | IH Europe | 0.2 | 1.8 | 6.5 | 10.0 |
| | | | E. Pptr. | | coll'td. | OH Europe | 0.05 | 3.0 | 9.0 | 14.0 |
| 87 | 267 | 66 | E. Pptr. | rocking | coll'td. | IH Europe | 0.5 | 4.0 | 10.7 | 15.0 |
| | | | E. Pptr. | | coll'td. | OH Europe | 0.01 | 0.2 | 1.2 | 2.0 |
| 88 | 600 | 64 | E. Pptr. | recip. | coll'td. | IH Europe[b] | 1.6 | 3 | 4 | 4.3 |
| | | | E. Pptr. | | coll'td. | OH Europe[b] | 0.25 | 1.2 | 3 | 3.8 |
| 94 | 250 | 66 | E. Pptr. | 5 trav. | coll'td | European | 1 | 3.4 | 7.6 | 11.0 |
| (41) | | | dry expan | | emitted | typical | 1.1 | 3.3 | 10.0 | 15.0 |
| 20 | 250 | 62 | wet baff | 2 trav. | emitted | at 122.6% cap., OF | | | 1.2 | 4.5 |
| | | | | | emitted | at 122.6% cap., OF | | | 0.3 | 1.85 |
| | | | | | emitted | at 120.0% cap., OF | | | 0.65 | 2.8 |
| (42) | 250 | 53 | wet wall | 2 trav. | emitted | | | | 8 | 12.5 |
| (44) | 250 | 61 | spray | 2 trav. | emitted | UF and OF | | | 3.5 | 7.0 |
| | 250 | 61 | spray | 2 trav. | emitted | UF and OF | | | 1.7 | 3.5 |
| | 250 | 53 | wet wall | 2 trav. | emitted | | | | 10.7 | 13.3 |
| 1 | 250 | 67 | wet wall | 3 trav. | emitted | UF and OF | 0.5 | 2.3 | 4.2 | 8 |
| 17 | 250 | 53 | wet wall | 2 trav. | emitted | (data in question) | | | | |
| 14 | 250 | 61 | wet baff | 2 trav. | emitted | UF and OF | | 2.3 | 10.0 | 15.5 |
| (43) | 300 | 55 | scrubber | rocking | emitted | UF and OF | | | | |
| (42) | 250 | 54 | dry expan | 2 trav. | emitted | UF and OF | | | | |

**Keys and Notes:**

IH - Hopper on inlet side of precipitator
OH - Hopper on outlet side of precipitator
OF - Overfire air in use
UF - Underfire air in use

a. Plant Numbers refer to Incinerator Data in Table J-1, Appendix J. References (numbers in parentheses) may be found in Section F, Chapter VII.

b. Coal being fired in furnace - with common flue

## TABLE VII-5

## OR EFFLUENT PARTICLE-SIZE DISTRIBUTION

| | Weight Fraction Less Than Indicated Effective Diameter (microns) | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2 μ | 4 μ | 6 μ | 8 μ | 10 μ | 20 μ | 40 μ | 60 μ | 80 μ | 100 μ | 200 μ | 300 μ | 400 μ | 500 μ | 600 μ | 700 μ | 800 μ |
| | 13.5 | 16.0 | 19.0 | 21.0 | 23.0 | 27.5 | 31.5 | | | | | | | | | | |
| | 23.5 | 30.0 | 33.7 | 36.3 | 38.1 | 45.0 | 52 | | | | | | | | | | |
| | 14.6 | 19.2 | 22.3 | 24.8 | 26.8 | 34.6 | 49 | | | | | | | | | | |
| 4 | 6.5- | 12- | 17 | 20- | 25- | 38- | 51- | 50- | 66 | 70- | | | | | | | |
| | 10.5 | 21 | 29 | 32 | 40 | 50 | 74 | 81 | 86 | 91 | | | | | | | |
| 3 | 4.5 | 8 | 12 | 15 | 17 | 30 | 48 | 59 | 68 | 73 | | | | | | | |
| 5 | 7 | 18 | 25 | 30.5 | 39.5 | 59 | 75 | 82 | 85 | 91 | | | | | | | |
| | | | | | | 33 | 54 | 66 | 74 | 80 | 93 | 95.5 | 97.2 | 98.2 | 98.6 | 99.1 | 99.3 |
| 6 | 2.8 | 7.2 | 8 | 12 | 13.8 | 20 | 22.5 | 30.0 | 34 | 62 | | | | | | | |
| 2 | 1.8 | 6.5 | 10.0 | 13.0 | 17.5 | 25.0 | 31 | 38 | 45 | 52 | | | | | | | |
| 05 | 3.0 | 9.0 | 14.0 | 17.5 | 20.4 | 32.0 | 40.0 | 48.0 | 56.0 | 64.0 | | | | | | | |
| 6 | 4.0 | 10.7 | 15.0 | 18.0 | 21 | 32 | 39 | 45 | 50 | 58 | | | | | | | |
| 01 | 0.2 | 1.2 | 2.0 | 2.8 | 3.5 | 7.0 | 11.0 | 15 | 20 | 31 | | | | | | | |
| 6 | 3 | 4 | 4.3 | 5 | 5.3 | 6.1 | 12 | 27 | 41 | 53 | 82 | | | | | | |
| 25 | 1.2 | 3 | 3.8 | 4.6 | 5.3 | 8.5 | 21 | 47 | 67 | 80 | 97.6 | | | | | | |
| | 3.4 | 7.6 | 11.0 | 14.0 | 17.5 | 29.0 | 40 | 50 | 58 | 68 | | | | | | | |
| | 3.3 | 10.0 | 15.0 | 20.0 | 24 | 39 | 60 | 69 | 71 | 77 | 93 | 97.5 | 98.8 | 99.2 | 99.5 | 99.6 | 99.8 |
| | | 1.2 | 4.5 | 9.5 | 15.2 | 49.5 | 82 | | | | | | | | | | |
| | | 0.3 | 1.85 | 3.5 | 7.8 | 26 | 75 | | | | | | | | | | |
| | | 0.65 | 2.8 | 7.0 | 13.5 | 41.7 | 85 | | | | | | | | | | |
| | | 8 | 12.5 | 15.5 | 17.8 | 42.4 | 56.8 | 70 | 74.5 | 90 | | | | | | | |
| | | 3.5 | 7.0 | 8.5 | 10.5 | 22.0 | 42.0 | 57 | 67 | 72 | 96.5 | 99.4 | 99.5 | | | | 99.6 |
| | | 1.7 | 3.5 | 7.0 | 11.6 | 30 | 47.4 | 59 | 62 | 70.5 | 88 | 93 | 95 | 95.8 | 96.5 | 97 | 97.5 |
| | | 10.7 | 13.3 | 15 | 16 | 45 | 56 | 78 | | | | | | | | | |
| | 2.3 | 4.2 | 8 | 11 | 37 | 78 | 92 | 98 | | | | | | | | | |
| | | | | | | 1.5 | 11 | 23 | 30 | 37 | 58 | 67 | 74 | 78 | | | |
| | 2.3 | 10.0 | 15.5 | 20 | 25 | 39 | 58.9 | 68 | 71 | 80 | 94.8 | 97.8 | 98.7 | 99.1 | 99.4 | 99.6 | 99.7 |
| | | | | | | | 22 | 50 | 69 | 78 | 93 | 96.5 | 98 | 98.8 | 99.2 | 99.3 | 99.6 |

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The curve for U.S.A. Installation No. 3 from the Walker and Schmitz data[1] is considered atypical, as the dust is so fine that its wet baffle APC system showed only a 10% collection efficiency — an abnormally low number. The data for Installation No. 2 was selected as our nominal distribution. In contrast to the tests on Installation No. 1, no overfire air was used at Installation No. 2. As discussed in Chapter V, an increase in the amount of small diameter combustible particulate would be expected in the absence of overfire air. Indeed, the dust of No. 2 is somewhat finer than that of No. 1. Thus, use of the article size distribution for No. 2 presents a more difficult but realistic collection problem. It is of interest that the furnace fly ash distribution appears much finer than the collected ash for the European plants (Table VII-5). Considering that the measured efficiencies of the European plants were all in excess of 95%, this difference cannot be accounted for as arising from the uncollected ash.

### b. Gaseous Species

Nominal values for gaseous pollutants are based on the emission data and analysis of refuse composition effects presented in Section V, summarized in Table VII-6. These values will be used in our subsequent estimate of control equipment performance for these pollutants.

## 4. Removal of Particulate Pollutants

### a. Settling Chambers

*(1) Introduction* A settling chamber (also called an expansion or subsidence chamber) is the simplest and least expensive of the APC systems now used on incinerators. It consists of a large refractory-lined chamber wherein the flue gases, without the necessity for temperature reduction, are slowed to permit gravity settling of the coarse particulate. In some cases, overpass and underpass half-walls or horizontal surfaces (skimmers) spanning between the sidewalls are installed with the intention of directing the gas flow. Increasingly, these chambers are supplemented by sprays to wet the walls, and the bottoms are wet (quiescent ponds) or sluiced (for fly ash removal) with water to minimize reentrainment of settled ash. The collection mechanism, however, is predominantly settling in all cases.

Calculation of settling velocities by Stokes' Law (and its various extensions into the "transition" regime for larger particles) leads to overestimation of a dry settling chamber's performance, as certain idealized conditions are assumed in the mathematical derivations.

## TABLE VII-6

## ASSUMED NOMINAL CONCENTRATIONS OF GASEOUS POLLUTANTS AT ENTRANCE TO APC DEVICE

| Type | Concentration ppm (volume) | Basis |
|---|---|---|
| $CO_2$ | 45,000 | ADL Estimated Average |
| CO | 1,500 | ADL Estimated Average |
| $NO_2$ | 15 | Rose et al, JAPCA 8 (4), 297–309 (1959) |
| NO | 35 | Rose et al, JAPCA 8 (4), 297–309 (1959) |
| Total Hydrocarbons (as $CH_4$) | 100 | Recent Tests on 3 New York City area incinerators |
| Total Organic Acids (as $CH_3COOH$) | 1 | Recent tests on 3 New York City area incinerators |
| Total Aldehydes (as HCHO) | 3 | Recent tests on 3 New York City area incinerators |
| $SO_2$ | 30 | ADL Estimated Average |
| $H_2SO_4$ | 50 | Recent tests on 3 New York City area incinerators |
| HCl | 60 | Recent tests on 3 New York City area incinerators |
| HF | <1 | |

The complications tending to lower the measured collection efficiency below the calculated value are:

- Nonsphericity of particles.
- Particle reentrainment due to turbulence (this can be minimized by use of a "wet-bottom" unit).
- Nonuniformity of particle density (the coarser particles tend to be lower in density).
- Particle-particle interactions ("hindered settling").
- Fallout of the very coarse particles prior to the chamber leaving a less easily settled dust in the gas stream.

*(2) Concept Evaluation* In general, settling velocities for homogeneous spherical particles can be calculated from the relation

$$u_t = \sqrt{\frac{4d(\rho_s - \rho_g)g}{3\rho_g C}} \qquad (1)$$

where

$u_t$ = terminal settling velocity, ft/sec

$d$ = particle diameter, feet

$\rho_s$ = density of particle, lb/ft$^3$

$\rho_g$ = density of gas, lb/ft$^3$

$g$ = gravitational constant, ft/sec$^2$

$C$ = drag coefficient, dimensionless

In the streamline-flow region (small particles), the drag coefficient is inversely proportional to the Reynolds number (Re):

$$C = \frac{24}{Re} = \frac{24\mu}{d u_t \rho_g} \qquad (2)$$

where

$\mu$ = viscosity of gas, lb/ft-sec

Re = Reynolds number $\frac{d u_t \rho_g}{\mu}$, dimensionless

In this streamline-flow region, combination of Equations (1) and (2) leads to Stokes' Law:

$$u_t = \frac{d^2(\rho_s - \rho_g)g}{18\mu} \quad (3)$$

For practical purposes, the streamline-flow region stops at about Re = 0.5 to 1.0. Thus, for 400°F gases and particulate densities of 2.5, Equation (2) – and thus Stokes' Law – is valid only up to diameters of about 90 microns. Above this region, we must use relationships other than Equation (2) to characterize the dependence of C on Re. For larger particles, the relation of Schiller and Naumann[3] indicates:

$$C = \frac{24}{Re}\left[1 + 0.15\, Re^{0.687}\right] \quad (4)$$

This relation is valid for $0.5 < Re < 800$.

Unlike the combination of Equations (1) and (2), the combination of Equations (1) and (4) no longer gives an explicit relation for $u_t$, but rather requires a trial and error solution for $u_t$. As an example, application of these relations to particles of density 2.0 and 3.0 in hot air at two temperatures leads to the settling velocities shown in Table VII-7. Note that for large particles, the effect of temperature is not very great. If we assume for incinerator dust the nominal particle-size distribution described above, a particle density of 2.5 g/ml, and a gas density and viscosity equal to that of air at the same temperature and pressure, we can calculate the expected performance of a typical settling chamber.

For a chamber 30 feet high with a mean gas residence time of 5 seconds (similar to that of the Hamilton Avenue incinerator in New York City for operation at 300% excess air), all particles falling faster than about six feet per second (or bigger than about 250 microns in diameter, from Table VII-7) should reach the bottom of the chamber during the five-second transit time. Particles falling at a slower rate should be deposited in proportion to the ratio of their settling velocities to the critical velocity (six feet per second for this chamber). The performance for the nominal size distribution would be as shown in Table VII-8. Such a "perfect" chamber would remove about 41% of the particulate weight. In practice, due to the four factors mentioned at the beginning of this chapter, a typical efficiency for a dry settling chamber is only 15%.[4] In Installation No. 1 as described by Walker and Schmitz,[1] the efficiency of such a chamber

## TABLE VII-7

## CALCULATED SETTLING VELOCITIES IN HOT AIR

(Spherical Particles)

| | Settling Velocity | | | |
|---|---|---|---|---|
| | (Density = 2.0 g/ml) | | (Density = 3.0 g/ml) | |
| **Diameter** | at 400°F | at 1500°F | at 400°F | at 1500°F |
| 30 microns | 0.1 ft/sec | 0.1 ft/sec | 0.2 ft/sec | 0.1 ft/sec |
| 40 | 0.2 | 0.1 | 0.3 | 0.2 |
| 50 | 0.4 | 0.2 | 0.5 | 0.3 |
| 60 | 0.5 | 0.3 | 0.8 | 0.4 |
| 70 | 0.7 | 0.4 | 1.1 | 0.6 |
| 80 | 0.9 | 0.5 | 1.4* | 0.8 |
| 90 | 1.2* | 0.7 | 1.6 | 1.0 |
| 100 | 1.4 | 0.8* | 1.8 | 1.2* |
| 200 | 3.7 | 2.8 | 5.1 | 4.0 |
| 300 | 6.3 | 5.4 | 8.4 | 7.5 |
| 400 | 8.8 | 8.2 | 11.6 | 11.2 |
| 500 | 11.1 | 11.0 | 14.6 | 14.9 |
| 600 | 13.4 | 13.8 | 17.5 | 18.5 |
| 700 | 15.6 | 16.5 | 20.2 | 22.0 |
| 800 | 17.6 | 19.2 | 22.9 | 25.4 |
| 900 | 19.7 | 21.8 | 25.4 | 28.7 |
| 1000 | 21.6 | 24.3 | 27.9 | 31.9 |

* The asterisk denotes the largest particle for which Stokes' Law was used; Schiller-Naumann extension was used for all larger particles.[3]

## TABLE VII-8

## CALCULATED PERFORMANCE OF A SETTLING CHAMBER

(Nominal Dust Size and Density, 30 Feet High, 5-Second Residence Time)

| | Weight of Particles Per 100 lb of Total Dust Entering | Removal Efficiency[a] | Weight of Particles Remaining | Weight of Particles Per 100 lb of Total Dust Remaining |
|---|---|---|---|---|
| < 1 micron | 9 lb | 0% | 9 lb | 15 lb |
| 1–2 | 5 | 0 | 5 | 9 |
| 2–5 | 7 | 0 | 7 | 12 |
| 5–10 | 6 | 0 | 6 | 10 |
| 10–15 | 5 | 0 | 5 | 8 |
| 15–20 | 3 | 0 | 3 | 5 |
| 20–30 | 5 | 1 | 5 | 8 |
| 30–40 | 3 | 3 | 3 | 5 |
| 40–50 | 4 | 5 | 4 | 7 |
| 50–100 | 8 | 15 | 7 | 12 |
| 100–200 | 8 | 50 | 4 | 7 |
| 200–300 | 5 | 90 | 1 | 2 |
| > 300 | 32 | 100 | 0 | 0 |
| | 100 lb | | 59 lb | 100 lb |

Removal Efficiency = 100–59 = 41%

[a] Based on settling velocities given in Table VII-7

is estimated at 21%. Operation with wet floors to prevent reentrainment can increase the efficiency, for example, to measured values of about 35% at Hamilton Avenue and to 31% at another installation.[5] A later test at the latter plant gave a 21% efficiency. Baffling can also raise the efficiency by increasing the probability of a particle encountering a solid surface.

The theoretical performance of other settling chambers can be calculated as above, with the aid of the settling velocities given in Table VII-7. Thus, for example, a shorter drop – say a 15-foot height with the same residence time at 400°F – would, in theory, remove all particles larger than 150 microns and have a total removal efficiency of about 47% (compared with the 41% figure for the chamber twice as high). Thus, the efficiency of these devices is low, but so is their pressure drop – typically below 0.15" $H_2O$. The major portions of this pressure loss occur at the inlet and a lesser amount at the outlet of the chamber, as a result of expansion and contraction losses.

*(3) Conclusions* If one knows the particle-size distribution in the +20 micron fraction of the dust, the performance of settling chambers can be roughly estimated from Stokes' Law and its modifications, but this leads to erroneously high estimates of efficiency. The use of wetted walls or floors improves the control effectiveness, but the effectiveness still falls short of the theoretical predictions. Design differences from one installation to another regarding turbulence will vary the amount of reentrainment and thus the collection efficiency.

Although settling chambers offer few serious operating difficulties, the system is not without problems. Dust removal, for dry chambers, requires periodic plant shutdown. Depending upon the required availability of the disposal capacity, this may or may not be a disadvantage. The alternative of water sluicing may create a water pollution problem or a corrosion problem (especially for recycled water systems), as dissolved acid gases and chloride ions build up in the water.

A second problem common to many settling chambers is the gross infiltration of tramp air. The resulting flue-gas-cooling and consequent quenching of combustion reactions may increase the emission of odorous air pollutants. This may be overcome by use of inorganic refractory sealants or by metal sheathing the chamber.

### b. Mechanical Collectors

*(1) Introduction* The principle of the cyclone device is shown in Figure VII-2. (Symbols are consistent with the nomenclature presented in the Design and Operation Section below.) The gas is given a spin (either by a tangential inlet or by guide vanes for an axial inlet), moves down the length of the

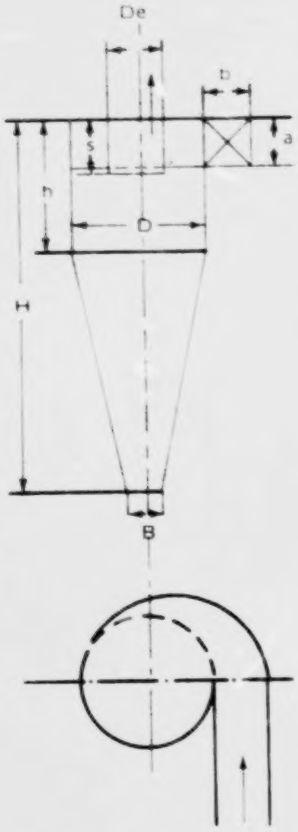


FIGURE VII–2 CONVENTIONAL CYCLONE, SHOWING DIMENSIONS USED IN CALCULATIONS

unit, usually reverses flow (sometimes assisted with guide vans to minimize pressure drop), and leaves through an axial exit pipe, spinning all the while. Because of the spin, the larger particles in the gas stream seek the outside of the gas stream, where they fall along the wall to a collection hopper. There are other modes of drawing off the peripheral particle-rich layer, but that which is illustrated is the most common. The wall can be operated wet or dry. For very high temperatures, these devices can be constructed with refractory linings. To permit ordinary steel and cast iron construction, however, the flue gases must be cooled to below 650°F (see Appendix B).

*(2) Concept Evaluation* In principle, one can calculate the collection efficiency of a cyclone for particles of any given diameter from any gas flow. These efficiencies are usually too high because of the reentrainment of particulate from the cyclone walls and out of the dust hopper. (This last condition is severely aggravated by small air inleaks if the hopper outlet is insufficiently sealed in a

system using induced draft.) Reentrainment from the particle-rich boundary layer at the walls is diminished by operating with wet walls, but at the risk of a hard cake buildup at the "wet-dry" boundary.

A good calculational approach in practice is to use the relationship obtained by applying Stokes' Law to the reasoning of Stairmand[6] in calculating $d_{50}$ (the particle size which a given installation should collect with 50% efficiency).

$$d_{50} = \frac{3}{u_i \phi} \sqrt{\frac{Q \mu D_e}{(2\pi)(\rho_s - \rho_g)(H - S)(D)}} \tag{5}$$

where

$$\phi = \frac{u_i'}{u_i} = \frac{-\sqrt{0.5\ D_e/(D-b)} + \sqrt{[0.5\ D_e/(D-b)] + [4GA/ab]}}{2GA/ab} \tag{6}$$

where:

$a$ = height of inlet duct: ft

$A$ = surface area of cyclone exposed to gases: $ft^2$

$b$ = width of inlet duct: ft

$d_{50}$ = particle-size collected with 50% efficiency: ft

$D$ = internal diameter of cyclone shell: ft

$D_e$ = internal diameter of exit pipe: ft

$G$ = friction constant (= 0.005 for gas cyclones): dimensionless

$H$ = overall internal height of cyclone: ft

$Q$ = gas flow rate: $ft^3$/sec

$S$ = internal height of exit pipe: ft

$u_e$ = gas velocity in exit pipe: ft/sec

$u_i$ = gas velocity in inlet duct: ft/sec

$u_i'$ = gas velocity at inlet radius $(D-b)/2$: ft/sec

$\mu$ = gas viscosity: lb/ft-sec

$\pi$ = a constant: 3.14159...

$\rho_g$ = gas density: $lb/ft^3$

$\rho_s$ = particle density: $lb/ft^3$

$\phi$ = $u_i'/u_i$, dimensionless

In the normal range of cyclone geometries, the following are approximately true:

$D_e = (3/4)D$ $S = (7/8)D$ $b = (3/8)D$

$H = 4D$ $a = (3/4)D$ $A = (9/4)\pi D^2$

Since $Q = abu_i$, we can make all the above substitutions in Equations (5) and (6) to obtain the simple equations:

$$d_{50} = .150 \sqrt{\frac{D^3\mu}{Q(\rho_s - \rho_g)}} \tag{5a}$$

and

$$\phi = 1.099 \tag{6a}$$

Having calculated $d_{50}$, one can obtain efficiencies for other particle diameters in the region of interest by using the graphical relationship of Barth,[7] given in Figure VII-3. Pressure drop can be calculated well by using the approach of Stairmand,[8] using the previously defined $\phi$ (see Equations 6 and 6a):

$$\Delta p = \frac{\rho}{2g} [u_i^2 \{1+4\phi^2(D-b)/D_e\} + 2u_e^2] \tag{7}$$

where:

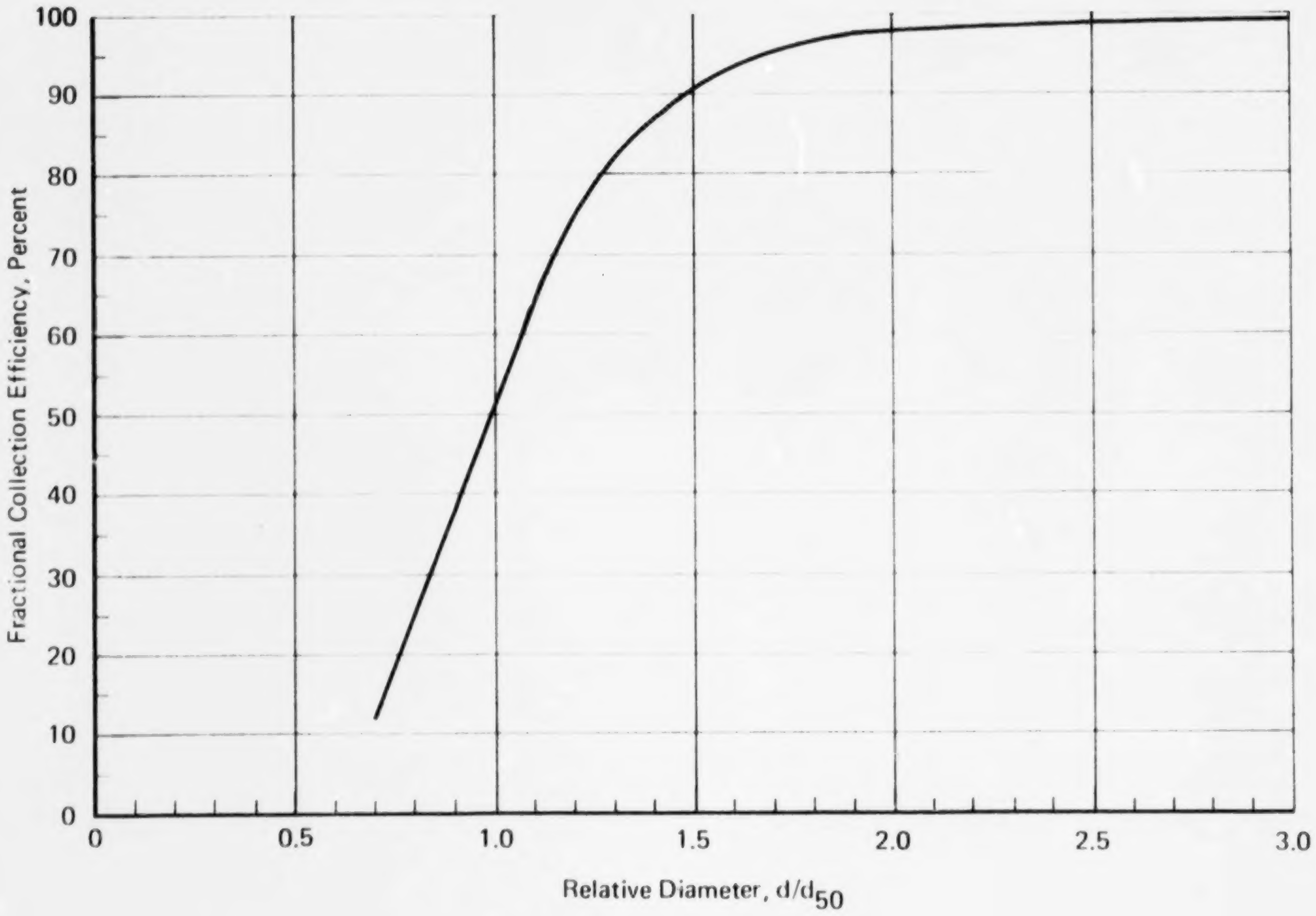
$g$ = gravitational constant, 32.17 ft/sec²
$\Delta p$ = pressure drop through inlet, cyclone, and exit, lb/ft²
$\rho$ = average density of gas plus suspended particles, lb/ft³

With some of the same substitutions as above, the equation simplifies to

$$\Delta p = 0.155\rho u_i^2 \tag{7a}$$

For illustration, if one applies the above relationships to the effluent (400°F) from an incinerator with a capacity of 250 tons per 24-hour day (TPD), for 3.5 inches of water pressure drop, the following designs obtain:

- a single cyclone 10.8 ft in diameter,
- two parallel units, each 7.6 ft in diameter, or
- 260 parallel units, each 8" in diameter – a multiple cyclone.



**Source:** Barth, W., Brennstoff-Wärme-Kraft, *8*,1 (1956).

FIGURE VII–3 FRACTIONAL COLLECTION EFFICIENCIES IN CYCLONES

These units differ in their collection efficiency for the nominal incinerator dust, because of the relationship indicated in Equation (5a): as more units are used, and the gas flow rate (Q) per unit decreases in proportion to the square of the cyclone diameter (D), the $d_{50}$ decreases in proportion to $\sqrt{D}$, and the collection efficiency increases.

Application of the three arrangements described above to the nominal dust size distribution and density described above yields the results of Table VII-9. Unfortunately, data to compare with the above estimates is limited to two installations. At Plant No. 4 (Appendix J, Table J-1), a two-day average collection efficiency of 84.5% was determined in 1961 on a multiple cyclone installation in Table VII-9. At Plant No. 70, tests showed somewhat more than a 62.3% efficiency for a system containing cyclones approximately two feet in diameter. Logarithmic interpolation of the results in Table VII-9, would have predicted about 78% for the nominal dust size distribution we have employed.

**TABLE VII-9**

**CALCULATED PARTICLE COLLECTION EFFICIENCIES OF THREE CYCLONE ARRANGEMENTS ON 400°F EFFLUENT FROM A 250-TPD INCINERATOR**

| Arrangement | No. of Units | Diameter of Each; ft | Flow Per Unit; acfm* | $d_{50}$; Microns | Total Calculated Collection Efficiency (%) |
|---|---|---|---|---|---|
| 1 | 1 | 10.8 | 98,000 | 13.3 | 69 |
| 2 | 2 | 7.6 | 49,000 | 11.2 | 71 |
| 3 | 260 | 0.67 | 380 | 3.3 | 83 |

---

* Assumes incinerator runs with 300% excess air

*(3) Conclusions* If one knows the particle-size distribution for an incinerator dust, one can adequately predict the pressure drop and particulate collection efficiency for any of the conventional cyclone configurations. The operational problems historically associated with cyclones are erosion, plugging, and air leakage. Erosion results from the constant scrubbing action of the unusually abrasive incinerator fly ash as it progresses through the cyclone. The inlet turning vanes on axial inlet systems and the collecting cones are the primary wear points. Plant reliability problems due to erosive failure of the cyclones may be minimized by:

- specifying hardened cast iron components in areas of wear;
- providing design specifications for access doors and replaceable components;
- maintaining an adequate spare parts inventory; and
- specifying sectioned cyclones to permit dampering-off of portions of the unit for repair.

Plugging problems are caused by the adherence of fly ash to the walls of the cyclone and subsequent buildup of hard deposits. In almost all cases, moisture is involved. In many plants using cyclones, the furnace gases are cooled to below 600°F with water sprays. Moist fly ash or entrained water droplets (which result from insufficient residence time for total evaporation), promise to cause problems.

A second type of plugging problem occurs with water-washed systems. In several plants, continuous water-washing of the cyclone walls has been done to minimize fly ash reentrainment and to slurry the ash for subsequent transfer operations. At some point, in such a system, there exists an area which is only intermittently wetted. This "wet-dry" boundary is the focus for particle buildup. There is little to be done about this problem, but to shut off the water except for intermittent fly-ash sluicing. Caution must be exercised in designing such intermittent systems to avoid plugging or other disfunction in the water system.

The third type of plugging caused by moisture occurs as a result of condensation of water vapor on the interior surfaces of the cyclone or outlet dust valves. With hot flue gas and proper insulation, this problem may be overcome.

Air leaking in drastically reduces cyclone efficiency, as the flow of air from the hopper is dust-laden and the flow through the dust valve disturbs the layer of particle-rich gases moving down the collecting cone. Installation and maintenance of hopper seals or dust valves readily solves these problems.

### c. Electrostatic Precipitators

*(1) Introduction* Electrostatic precipitators are different from all other types of dust collectors; in that the separating force applied to the dust particles is generated by the interaction of electrical charges placed upon the surface of the dust particles with an electrical field, through which the dust-laden gas passes.

The single-stage electrostatic precipitator is the type used most frequently on large-scale industrial gas-cleaning applications, such as the treatment of effluent gases from municipal incinerators. In order to permit the use of low cost carbon steel construction, the flue gases must be cooled to temperatures less than 650°F (see Appendix B). Figure VII-4 is a schematic drawing showing the arrangement of electrodes and the direction of gas flow in this type of precipitator.

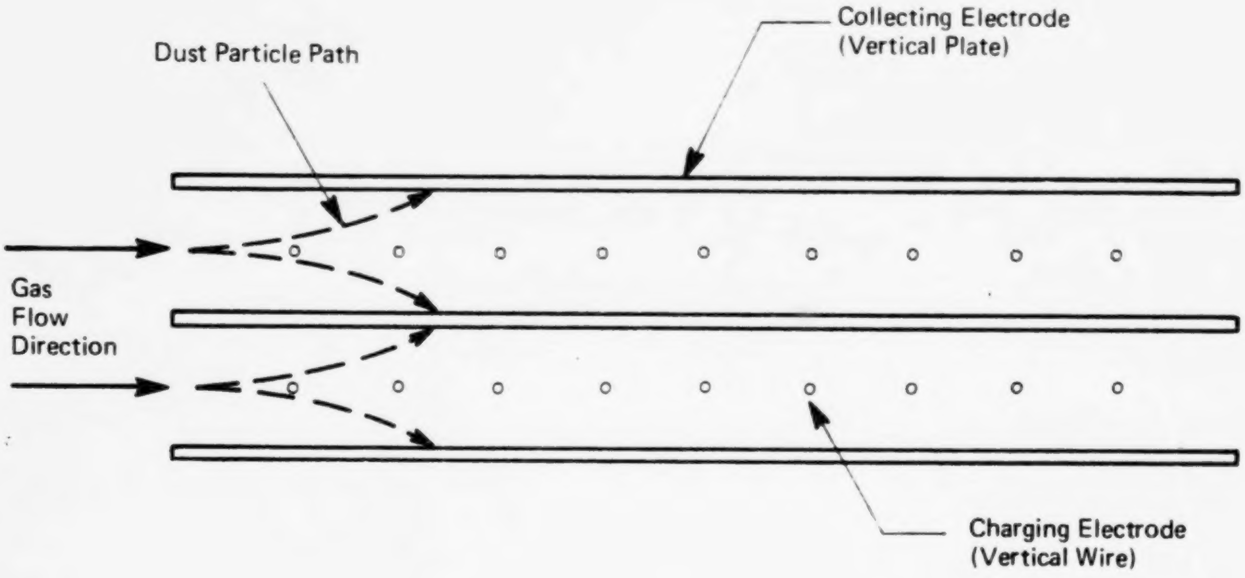


FIGURE VII–4 SCHEMATIC DRAWING OF ELECTRODE ARRANGEMENT IN A SINGLE-STAGE ELECTROSTATIC PRECIPITATOR

One of the two electrodes is the collecting electrode, typically in the form of vertically-disposed, parallel metal plates, from six to twelve inches apart. The charging, or corona electrodes, consist of a series of wires or other slender metal elements placed in a row centered between the collecting plates, as shown in Figure VII-4.

The strength of the electrical field between the discharge electrode wires and the collecting plate electrodes is maintained at a sufficiently high level, so that a corona discharge occurs on the surface of the wires. In the case of the negative corona system, used for all industrial precipitator applications, the electrical discharge produces a large number of negatively-charged ions which effectively fill the entire space between the collecting plates. Upon entering this ion-filled space, the dust particles receive a large negative electrical charge (proportional to the surface area of the dust particle). The negatively-charged dust particles are then moved toward the positively-charged (or grounded) collecting plates, influenced by the electrical field present in the system.

The dust particles ultimately touch the surface of the collecting electrode, are deposited on the plates, and subsequently on the surface of the previously-collected dust particles. This dust layer grows in thickness as particles continue to be removed from the gas stream. At predetermined intervals, the collecting plates are mechanically rapped in order to dislodge the layer of collected dust. Typically, the collected dust particles from the collecting electrode are in the form of large sheets of fairly well consolidated dust which simply fall, under the influence of gravity, into collecting hoppers located beneath the electrode section of the precipitator. Some of the dust, however, may be reentrained by the flowing gas and swept into the effluent gas stream, to be emitted subsequently at the stack.

*(2) Concept Evaluation* Since the first successful commercial application of electrostatic precipitation to the removal of particulates from waste industrial gases almost sixty years ago, a large body of theoretical and experimental information has been accumulated. This information describes the performance of electrostatic precipitators. These data also relate most of the independent variables of precipitator design and operating conditions to the foremost dependent variable of interest: – collection efficiency.

The following is a list of the more important variables which have been shown to affect the design and operation of electrostatic precipitators.

(a) Input Characteristics

- Volume flow rate and composition of the gas to be treated
- Gas temperature (and hence viscosity)
- Particle loading
- Particle size distribution
- Electrical resistivity of particles

(b) Primary Parameters Specified by the Precipitator Designer

- Gas velocity
- Required charging and collection electrode shape – spacing and area to meet specified design efficiency

- Height of collection electrodes – There are several fixed heights and the choice is usually determined by the total cfm treated. Choice of the height specifies the total length, and therefore the gas residence time; since both total collection electrode area and gas velocity have already been chosen.

- Degree of high tension sectionalization

- Type of rectifier – Depending upon the application, desired efficiency, etc., the degree of high tension sectionalization will be chosen and the power supplies selected to meet the power requirements

- The frequency, intensity, and point of application of collecting electrode rappers.

There is no overall generalized design correlation of the above design parameters (as well as other unmentioned variables of less importance) to the collection efficiency for electrostatic precipitators. If such a complete correlation were available, the design of precipitators would be reduced to a straightforward computation. Not only is the relationship between these independent variables and collection efficiency understood imperfectly at present, but also the performance of an electrostatic precipitator may be dependent upon additional variables not presently perceived.

Early experimental studies of electrostatic precipitators indicated that, with other factors held constant, the collection efficiency varied exponentially with residence time. This relationship has been the basis for a number of general and simplified design equations which can be used for predicting performance of electrostatic precipitators and has come to be known as the Deutsch Equation.[9] This equation relates collection efficiency to the collecting plate area, volumetric flow rate of gas, charging and collecting field strengths, particle size, and gas viscosity:

$$\text{Collection efficiency} = 1 - e^{-w\left(\frac{A}{V}\right)} \qquad (8)$$

where:

A = collecting plate area, $cm^2$
V = volumetric flow rate of gas, $cm^3/sec$
w = particle migration or drift velocity, cm/sec

The drift velocity of a particle is defined[10] as follows:

$$w = \frac{E_c E_o d C}{4\pi\mu} \tag{9}$$

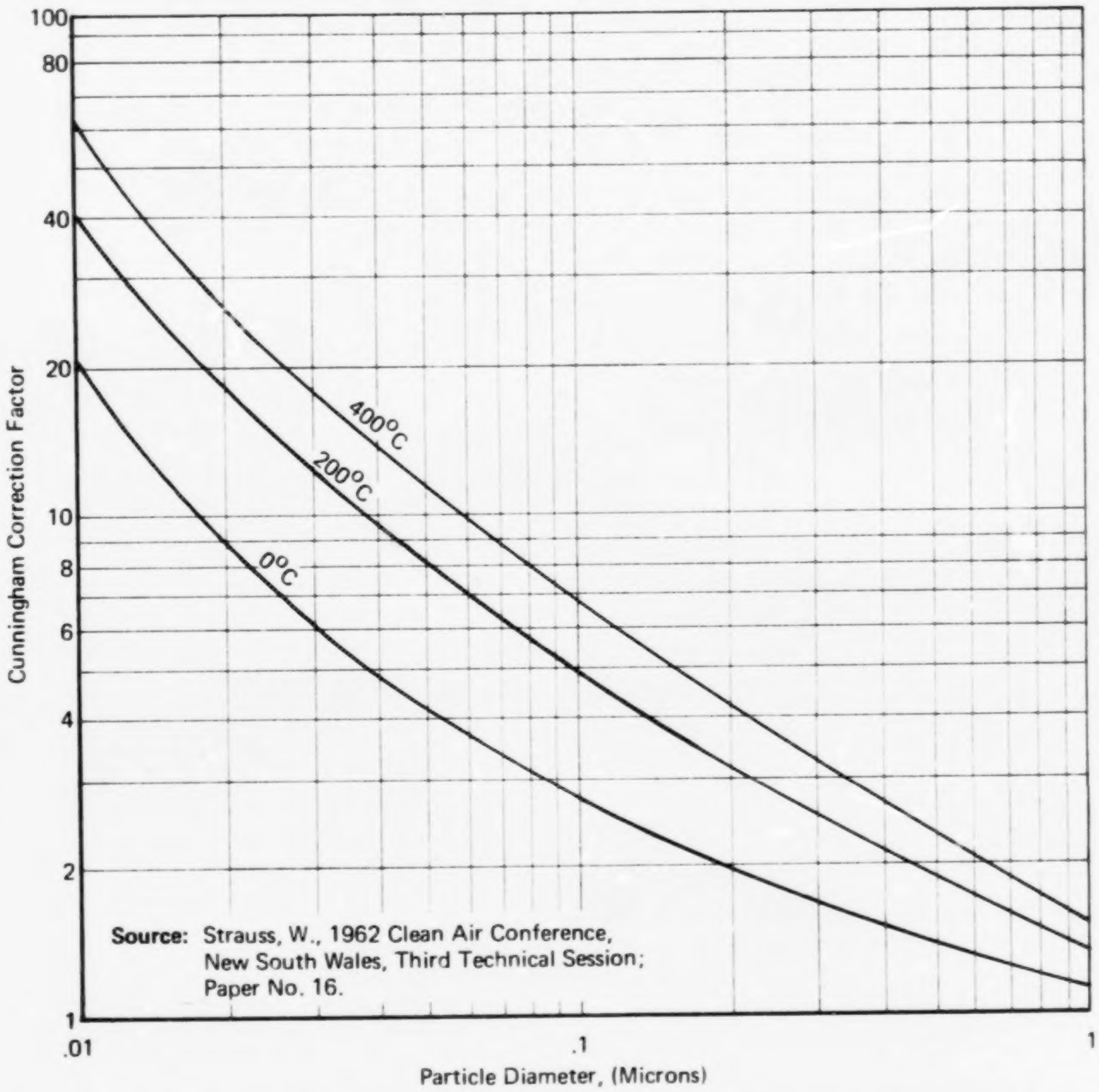
where:

$w$ = drift velocity, cm/sec
$E_c$ = charging field strength, electrostatic volts/cm
$E_o$ = collecting field strength, electrostatic volts/cm
$d$ = particle diameter, cm
$C$ = Cunningham correction factor, dimensionless (the ratio of the actual settling velocity for fine particles to that predicted by Stokes' Law – see Figure VII-5).
$\mu$ = gas viscosity, g/cm-sec
$\pi$ = a constant, 3.14159...

The Deutsch Equation has been shown to specify adequately the shape of the collection efficiency curve as a function of one of the other independent variables, except in the particle-size range below 0.5 micron. For these small particles, diffusion charging becomes the predominant mechanism for particle charging (versus field charging for the larger particulate). Equations describing collection characteristics where diffusion charging is important have not yet been fully developed or tested. Therefore, errors must be expected for theoretical predictions in the submicron particle-size range, using the Deutsch Equation. Even for larger particles, the efficiency curve must still be located by practical experience with past performance of similar electrostatic precipitators operating on a similar gas-particulate system.

Wheelabrator Corporation obtained information on our behalf from Lurgi Apparatebau GmbH (its European electrostatic precipitator licensor) for the performance of five selected electrostatic precipitators, operating on municipal incinerators located in Germany, France, and England.[12,13,14,15,16] These data are principally summaries of test data obtained by agencies such as Technischer Uberwachungs-Verein (TUV), in Germany, and descriptions of the plant equipment, operating history, refuse type, etc. The five facilities selected were:

- Munich-North I, Germany;
- Düsseldorf, Germany;
- Paris, France;
- Tourcoing, France; and
- Birmingham, England.



**Source:** Strauss, W., 1962 Clean Air Conference, New South Wales, Third Technical Session; Paper No. 16.

**FIGURE VII–5 CUNNINGHAM CORRECTION FACTOR FOR PARTICLES IN AIR AT VARIOUS TEMPERATURES**

These data neither explicitly report nor permit estimation of the basic design and operating parameters of these precipitators, such as the collecting plate area, electrical field strength, etc. The only publicly available data are those published by Andritzky,[2] for the Munich-North I precipitator. From these data, it was possible to compute the apparent drift velocity (w) corresponding to the guarantee for this facility, as well as that actually measured during operation. This precipitator is reported to have an effective collecting electrode area of 4,525 $m^2$ and a free cross-sectional area of 61.2 $m^2$. Table VII-10 shows the apparent drift velocity, expressed in cm/sec, for both the guaranteed and actually-measured operating conditions, as well as other characterizing data.

The apparent drift velocity is a direct measure of the performance of an electrostatic precipitator. The operating efficiency of the collector increases as the value of w increases. From Table VII-10, it can be seen that:

- The performance of the Munich-North I precipitator is considerably higher than guaranteed.

- The ratio of the actual apparent drift velocity to the guaranteed drift velocity ranges from 1.23 to 1.49 for operation with coal alone, as well as with a mixture of coal and refuse. This suggests that the designers can predict the performance of a given precipitator, on the basis of past experience in the design and performance of electrostatic precipitators for this type of application.

- When operating on the effluent from an incinerator which is burning refuse alone, an electrostatic precipitator has a lower collection efficiency (or must be larger in size for a given collection efficiency) than it would have in the case of an incinerator operating on a mixture of coal and refuse or on coal alone. This implies that electrostatic precipitators may have to be significantly larger (and more expensive) for a municipal incinerator than for a coal-fired steam boiler, if everything else is held constant (such as volumetric flow rate of gas, efficiency, temperature, etc.). However, more detailed test work, such as that reported by Andritzky,[2] is required in order to confirm this.

None of the test reports for the five European precipitators presented the particle-size distribution analysis for the particulates either entering or leaving the electrostatic precipitators, although recent data on the collected dust is presented above (Plant No. 88, Table VII-5). Therefore, there is insufficient information to

## TABLE VII-10

## PERFORMANCE OF ELECTROSTATIC PRECIPITATOR OPERATING ON MUNICH–NORTH I INCINERATOR IN WEST GERMANY (ref. 2)

| Location | Fuel | Gas Velocity m/sec | Guaranteed Efficiency (%) | Actual Efficiency (%) | Apparent Drift Velocity, w(cm/sec) Corresponding to Guarantee | Apparent Drift Velocity, w(cm/sec) Corresponding to Actual Measured | Apparent Drift Velocity, w(cm/sec) Ratio $\left(\frac{w_{actual}}{w_{guaranteed}}\right)$ |
|---|---|---|---|---|---|---|---|
| Munich | Coal | 0.845 | 97.94 | 99.56 | 4.40 | 6.21 | 1.41 |
| Munich | Coal | 0.871 | 97.49 | 98.67 | 3.42 | 5.10 | 1.49 |
| Munich | Coal & Refuse | 1.132 | 99.25 | 99.75 | 7.50 | 9.20 | 1.23 |
| Munich | Refuse | 0.490 | – | 99.89 | – | 4.51 | – |

permit an explicit test of the Deutsch Equation to predict the collection efficiency of these electrostatic precipitators, as a function of particle size for comparison with the overall collection efficiencies actually measured.

In order to explore the utility of the Deutsch Equation, however, two different particle-size distributions were assumed for the particulates entering the electrostatic precipitator at Munich-North I, and the collection efficiency of that precipitator was calculated. The distributions chosen were those previously shown in Figure VII-1, for U.S.A. Installation No. 2 and for Andritzky's European distribution.

Table VII-11 compares the measured collection efficiency of the Munich-North I incinerator/electrostatic precipitator system as reported in the test reports, with the value predicted from the Deutsch Equation (using the two particle-size distributions previously described).

### TABLE VII-11

### COMPARISON OF MEASURED AND PREDICTED COLLECTION EFFICIENCY MUNICH-NORTH I USING THE DEUTSCH EQUATION

| | |
|---|---|
| Measured value (TUV test data) | **99.89%** |
| Predicted values based upon: | |
| 1) German refuse incinerator particle-size distribution (Andritzky) | **99.68%** |
| 2) U.S.A. refuse incinerator particle-size distribution (Walker-Installation No. 2) | **97.93%** |

Using the particle-size distribution for particulates in the effluent from a municipal incinerator operating on town refuse in Germany provides the closer match between predicted value and actual measured value for the Munich incinerator.

The calculation for the collection efficiency of the Munich-North I incinerator/electrostatic precipitator system with Andritzky's particle-size distribution is shown in Table VII-12. From inspection of Table VII-12, it can be seen that the collection efficiency for all particles greater than 2 microns approaches 100%. Therefore, the differences in the predicted collection efficiency of this precipitator using these two particle-size distributions result purely from the difference in the quantity of fine particles (less than 2 microns). However, no practical methods and/or devices for determining the size distribution of solid particulates below approximately 2 microns are presently available. As a result, particle-size

## TABLE VII-12

## PREDICTION OF COLLECTION EFFICIENCY OF MUNICH ELECTROSTATIC PRECIPITATOR – BASED ON ANDRITZKY'S PARTICLE–SIZE DISTRIBUTION FOR GERMAN REFUSE

| Particle Diameter Range, microns | Weight of Particles Entering Precipitator Based on 100-lb Total, lb | Mass Mean Particle Diameter, microns | Cunningham Correction Factor (C) | Drift* Velocity cm/sec | Collection Efficiency, percent | Weight of Particles Collected, lb |
|---|---|---|---|---|---|---|
| 0.02 – 0.15 | 0.19 | 0.095 | 4.2 | 1.10 | 62.2 | 0.12 |
| 0.15 – 0.30 | 0.30 | 0.23 | 2.5 | 1.59 | 75.6 | 0.23 |
| 0.30 – 0.50 | 0.5 | 0.42 | 1.8 | 2.14 | 85.1 | 0.42 |
| 0.50 – 1.00 | 1.0 | 0.77 | 1.4 | 2.98 | 92.85 | 0.93 |
| 1.00 – 2.00 | 2.0 | 1.5 | 1.2 | 4.96 | 98.78 | 1.98 |
| 2.00 – 4.00 | 3.0 | 3.0 | 1.0 | 8.28 | 99.93 | 3.00 |
| 4.00 – 7.00 | 5.0 | 5.5 | 1.0 | 15.18 | 100.00 | 5.00 |
| > 7.00μ | 88.0 | Large | – | Large | 100.00 | 88.00 |
|  |  |  |  |  |  | 99.68 |

Calculated Collection Efficiency = 99.68%
Measured Collection Efficiency = 99.89%

* Using Equations (8) and (9), neglecting diffusion charging

distributions below about 5 microns are typically not measured, but obtained by extrapolation. Such procedures introduce considerable uncertainty, since the extrapolation occurs in the area of particle-size distribution, which totally affects the prediction of collection efficiency of electrostatic precipitators. Also, this is the size range where diffusion charging must be considered. Even if high-resolution size-distribution measuring instruments were developed and if one could account for the diffusion charging phenomena, problems would still persist in calculating the efficiency. The distribution needed is that of particulate as it enters the precipitator; agglomeration or attrition associated with the sampling process will distort the results.

A number of domestic municipal incinerators are either presently equipped with electrostatic precipitators, or will be so equipped in the future. These precipitators include both full-scale units, and smaller experimental or demonstration units:

- *New York/Southwest Brooklyn Station – Wheelabrator* – This is a full-scale electrostatic precipitator installed on a 250-ton/day refractory wall, traveling grate-type municipal incinerator. This precipitator began operation on August 5, 1969. The incinerator produces approximately 170,000 actual cfm of effluent gas at 1600°F. This gas stream is passed through a water spray cooling tower which conditions the gas prior to the electrostatic precipitator inlet. The precipitator receives 130,000 actual cfm of gas at 550°F. The precipitator is designed to remove approximately 95% of the particulates in the incinerator's effluent gas stream, which will result in a solids content in the stack effluent of approximately 0.175 lb per 1,000 lb of gas, at 50% excess air.

- *New York City/South Shore Station – Research Cottrell* – This equipment is similar in size and efficiency to the Wheelabrator precipitator. It is anticipated that the unit will be started up in late fall, 1969.

- *Stamford Connecticut – Universal Oil Products (Air Correction Division)* – The electrostatic precipitator at this facility is presently being constructed and will clean the gases leaving a full-scale bulky waste, batch-feed, cruciform furnace installation.*

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* This effort is jointly supported by HEW – Bureau of Solid Wastes Management and the municipality.

- *Chicago, Illinois – Rothe Muehle-Walther* – Electrostatic precipitators supplied by this German firm are to be installed on four 400-ton/day waterfall furnaces. Metcalf and Eddy have engineered the facility, and construction is being carried out by the International Boiler Works (Stroudsburg, Pennsylvania). The incinerator is based on the design and grate system supplied by Martin of Munich, Germany. This facility is presently under construction.

- *Braintree, Massachusetts – Wheelabrator* – The two, 125-ton/day municipal incinerator furnaces will be supplied with electrostatic precipitators. Construction began in September 1969, and these two waterwall furnaces are scheduled to be operating by the end of April 1970.*

- *Northeast Dade County/Miami, Florida – Wheelabrator* – An electrostatic precipitator is under construction at this 300-ton/day refractory wall municipal incinerator facility. It is scheduled to be in service in January 1970. This plant is the first of six identical installations to be equipped with electrostatic precipitators serving the greater Miami area.

- *Rochester, New York/Eastman Kodak Corporation – Wheelabrator* – Construction of an electrostatic precipitator for Kodak's 300 ton/day waterwall furnace (burning industrial refuse) is scheduled to begin operations in early spring, 1970.

- *Pilot Studies – Research Cottrell* – A number of pilot programs are under way at the time of this writing at the Greenpoint incinerator in New York City** and at Freeport, Long Island.*

Foreign installations include:

- *Montreal, Quebec – Research Cottrell* – There are four furnaces (300 tons/day each) under construction. They will generate steam and will have 95% efficiency precipitators installed. Start-up is scheduled for April 1970.

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* These efforts are being jointly supported by HEW – Bureau of Solid Wastes Management and the municipality.

** These efforts are being jointly supported by HEW – National Air Pollution Control Administration and the municipality.

- *Hamilton, Ontario – Wheelabrator –* Construction of two electrostatic precipitators to service the two 300-ton/day waterwall Babcock-Wilcox incinerators is scheduled to begin in 1970, with the precipitators scheduled to be in service in August 1970.

- A large number of electrostatic precipitators are operating on municipal incinerators in Europe. These incinerators reflect both refractory wall furnace construction (used for refuse disposal only), and the waterwall-type, which also recovers heat as steam for heat and electrical power. In Europe, these two types of incinerators operate on town and/or industrial refuse, burned either alone or in conjunction with coal-firing. Table VII-13 characterizes a large number of incinerator-precipitator systems which have been constructed in Europe.

Because of the metal construction and low pressure drop of an electrostatic precipitator, this air pollution control device does not limit the way in which a municipal incinerator can be operated, with regard to total gas flow, furnace temperature, particulate concentration in the exit gas stream, etc. Although considerable latitude in incinerator/precipitator operation is permitted, the actual collection efficiency of an electrostatic precipitator is a rather sensitive function of the main operating characteristics of the incinerator and its effluent gas:

- Size distribution of particulates;
- Concentration of particulates;
- Electrical resistivity of particulates;
- Gas flow rate; and
- Gas temperature.

Therefore, an electrostatic precipitator must be conservatively designed for assurance of guaranteed performance over the full range of possible operating conditions.

One of the main contingencies in incinerator operation, perhaps the most difficult to allow for in the design of an electrostatic precipitator, is the production of high concentrations of carbon particles: The incomplete combustion of paper results in large flakes of carbonaceous ash, and the combustion of large quantities of refuse components, with a high volatile carbon content, results in large numbers of extremely fine carbon particles. Because of the low electrical resistivity of carbon, these particles quickly lose their charge upon deposition on the collecting plates in the precipitator, and the particles are therefore reentrained

## TABLE VII-13

## ELECTROSTATIC PRECIPITATORS INSTALLED ON M

| Installation | Furnace/ Precipitator | Incinerator Capacity, Metric Tons Per Day | Fuel[a] |
|---|---|---|---|
| Munchen-Sud | 1/1 | 960 | M + C |
| Solingen | 2/2 | 2 x 200 | M |
| Iserlohn | 2/2 | 2 x 192 | M |
| Unterland, Switzerland | 2/1 | 2 x 75 | M + S |
| Ford, Saarlouis | 2/1 | 72 + 48 | I |
| Kassel | 1/1 | 240 | M |
| Ford, Koln | 2/1 | 2 x 68 | I |
| Wien-Spittelau | 2/2 | 2 x 350 | M |
| Paris II, Ivry | 2/4 | 2 x1200 | M |
| Leverkusen | 2/2 | 2 x 200 | M |
| New York, New York, USA | 1/1 | 290 | M |
| Kobe City, Japan | 2/1 | 2 x 150 | M |
| Yokohama City, Japan | 3/3 | 3 x 150 | M |
| Kobe City, Japan | 3/3 | 3 x 150 | M |
| Sutton Goldfield, GB | 1/1 | 100 | M |
| Dawsholm-Glasgow, GB | 2/2 | 2 x 192 | M |
| Rotterdam-Botlek | 6/6 | 6 x 450 | M |
| Berlin-Ruhleben | 2/1 | 2 x 384 | M |
| Kassel | 1/1 | 240 | M |
| York, GB | 1/1 | 100 | M |
| Braintree, Mass., USA | 2/2 | 2 x 120 | M |
| Kawasaki, Japan | 3/3 | 3 x 150 | M |
| KVA Zurich (1927) | 1/2 | | |
| Hamburg (1930) | 3/3 | 3 x 160 | |
| Essen-Karnap | 4/4 | 4 x 480 | M |
| Munchen-Nord | 2/2 | 2 x 600 | M + C |
| Munchen-Nord | 1/1 | 960 | M + C |
| Opel, Bochum | 1/1 | 50 | I |
| Frankfurt/Main | 2/2 | 2 x 300 | M |
| Frankfurt/Main | 2/2 | 2 x 300 | M |
| Dusseldorf | 4/2 | 4 x 240 | M |
| Ludwigshafen | 2/2 | 2 x 200 | M |
| Darmstadt | 2/2 | 2 x 200 | M |
| Paris I, Issy Moul. | 4/8 | 4 x 400 | M |
| Mannheim | 2/2 | 2 x 430 | M |
| Berlin | 4/2 | 4 x 300 | M |
| Opel, Russelsheim | 1/1 | 42 | I |
| Birmingham, GB | 1/1 | 230 | M |
| Osaka City, Japan | 4/2 | 4 x 150 | M |
| Edegawa/Tokyo-Met. | 3/3 | 3 x 200 | M |
| Oslo, Norway | 2/2 | 2 x 156 | M |
| Bayer Leverkusen | 1/1 | 300 | I |
| Tourcoing, France | 9/2 | 2 x 140 | M |
| Nurnberg | 3/3 | 3 x 300 | M |
| Biel, Switzerland | 1/1 | 60 | M |

[a] Incinerator Fuel: M = Municipal Refuse; I = Industrial Refuse; C = Coal; S = Sludge

## TABLE VII-13

## STATIC PRECIPITATORS INSTALLED ON MUNICIPAL INCINERATORS

| cinerator Capacity, etric Tons Per Day | Fuel[a] | Grate System | Flow Rate, Thousands of m³/hr | Gas Temp. (°C) | Guaranteed Collection Efficiency Percent |
|---|---|---|---|---|---|
| 960 | M + C | Martin | 830. | 186 | 98 |
| 2 x 200 | M | Von Roll | 2 x 125. | 300 | 99 |
| 2 x 192 | M | Babcock | 2 x 97. | 280 | 98.5 |
| 2 x 75 | M + S | LW-Etagenofen | 1 x 45. | 350 | 97.5 |
| 72 + 48 | I | Babcock | 83.5 | 300 | 99 |
| 240 | M | "Dusseldorf" | 130. | 280 | 98 |
| 2 x 68 | I | Babcock | 78.5 | 300 | 98 |
| 2 x 350 | M | W. Biro, Syst. Martin | 3 x 139. | 200 | 99.6 |
| 2 x1200 | M | Martin | 2 x 562. | 230 | 99 |
| 2 x 200 | M | Von Roll | 2 x 128. | 300 | 99 |
| 290 | M | Combustion Engineering | 225. | 300 | 95 |
| 2 x 150 | M | | 54. | 300 | 97.78 |
| 3 x 150 | M | | 3 x 84.6 | 300 | 97.78 |
| 3 x 150 | M | | 3 x 72. | 300 | 97.78 |
| 100 | M | Heenan + Froude | 190. | 300 | 94.29 |
| 2 x 192 | M | Heenan + Froude | 2 x 315. | 300 | 98.13 |
| 6 x 450 | M | "Dusseldorf" | 6 x 143. | 350 | 98.4 |
| 2 x 384 | M | "Dusseldorf" | 294.1 | 235 | 99.34 |
| 240 | M | "Dusseldorf" | 129.6 | 280 | 98 |
| 100 | M | Heenan + Froude | 160. | 300 | 96 |
| 2 x 120 | M | Riley Stoker | 2 x 54.5 | 315 | 93 |
| 3 x 150 | M | | 3 x 67.1 | 300 | 97.73 |
| | | Bamag | 112. | 250 | 92 |
| 3 x 160 | | Lurgi | 3 x 30. | 200 | 94-97 |
| 4 x 480 | M | Babcock | 4 x 398. | 180 | 98.5 |
| 2 x 600 | M + C | Martin | 2 x 228. | 170 | 99.53 |
| 960 | M + C | Martin | 755. | 140 | 99.5 |
| 50 | I | Von Roll | 38.2 | 300 | 99.35 |
| 2 x 300 | M | Von Roll | 2 x 147. | 325 | 98 |
| 2 x 300 | M | Von Roll | 2 x 185. | 325 | 99 |
| 4 x 240 | M | "Dusseldorf" | 2 x 152. | 260 | 99 |
| 2 x 200 | M | Von Roll | 2 x 125. | 300 | 99 |
| 2 x 200 | M | Von Roll | 2 x 125. | 300 | 99 |
| 4 x 400 | M | Martin | 4 x 238. | 270 | 99 |
| 2 x 430 | M | KSG | 2 x 137. | 210 | 99.35 |
| 4 x 300 | M | "Dusseldorf" | 2 x 211. | 220 | 99 |
| 42 | I | Von Roll | 38.5 | 300 | 99 |
| 230 | M | Heenan + Froude | 176. | 200 | 98.75 |
| 4 x 150 | M | Taguma Boiler MFG | 2 x 174. | 350 | 93.33 |
| 3 x 200 | M | Taguma Boiler MFG | 3 x 141. | 350 | 96.67 |
| 2 x 156 | M | Ma. Fa. Esslingen | 2 x 76.3 | 300 | 98 |
| 300 | I | Drehrohrofen | 129. | 300 | 99.5 |
| 2 x 140 | M | Stein + Roubaix | 2 x 148. | 340 | 96 |
| 3 x 300 | M | Von Roll | 3 x 188. | 300 | 99 |
| 60 | M | Von Roll | 34. | 300 | 98.5 |

= Coal; S = Sludge

B

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in the gas stream. These particles go through the cycle of recharging, reprecipitation, charge loss, and reentrainment until a substantial percentage of them is lost from the precipitator. Measures to improve the collection of such particles include special collecting-plate design and the provision of low-efficiency cyclones on the exit gas stream from the precipitator, to collect large carbon particles from paper combustion and carbon agglomerates.

To provide an indication of the characteristics of incinerator ash resistivity, samples of collected ash from several European incinerators were secured and resistivity tests were performed. These data, supplemented by several value figures from the literature, are presented in Table VII-14. The results indicate that relative incinerator ash resistivity (especially in the larger particles) is low; a problem which supports the conclusion that electrostatic precipitators on incinerators may be larger and more costly than for other gas-cleaning applications.[18] It must be recognized, however, that the "true" parameter is the resistivity of the dust cake *in the precipitator.* As a result, the conclusion above is inferred, rather than factual.

*(3) Conclusions* The performance of electrostatic precipitators can be roughly estimated, given the particle-size distribution data below 2 microns. This information is lacking for incinerator dust, necessitating uncertain but critical extrapolations. In addition, precipitator theory needs refinements, to describe the collection behavior of submicron particles. Based on extrapolated particle-size distribution, it appears that U.S. fly ash may be more difficult to collect vis-à-vis European dust. This reflects the larger fraction of very fine particulate in the United States ash.

Operating experience on the five European plants visited has been excellent; problem areas have been the flue gas conditioning and ash removal systems, rather than the precipitator (see Appendix E). Potential problems with many U.S. incinerators could result from deposition of tar aerosols or dust, which could adhere to the collecting plates. However, this has not been reported in the tests to date. Problems with reentrainment of collected particulate (partly due to low resistivity) may be moderated by use of a low-pressure-drop cyclone following the precipitator. Such units have been shown effective in capturing the large agglomerated particles which result from the process.[18]

### d. Filters

*(1) Introduction* The fabric filter, when properly designed and operated, surpasses other conventional APC systems in the removal of particulate matter. Any porous material can, in principle, be used to clean particle-bearing gas streams. However, tubes (6-12 inches in diameter and 6-40 feet long) of woven

## TABLE VII-14

## BULK RESISTIVITY MEASUREMENTS ON INCINERATOR FLY ASH[1,17,18,19,20]

| Source | Type[a] | Temperature | Dew Point | Resistivity (ohm-cm) | Remarks |
|---|---|---|---|---|---|
| Birmingham, England (Ref. 13) | C | 500°F | 131°F | $3 \times 10^6$ | |
| Dusseldorf, West Germany (Ref. 12) | C | 482 | 113 | $6 \times 10^7$ | |
| Munich (North 1), West Germany (Ref. 14) | C | 320 | 77 | $2 \times 10^9$ | Coal and Refuse Firing |
| Tourcoing, France (Ref. 16) | C | 392 | 130 | $7 \times 10^6$ | |
| S. W. Brooklyn, New York | C | 550 | 104 | $8 \times 10^5$ | |
| New York (Ref. 17) | A | 300 | 115 | $1.5 \times 10^8$ | Minus 300μ Fraction |
| New York (Ref. 17) | A | 400 | 115 | $1.1 \times 10^{10}$ | |
| New York (Ref. 17) | A | 600 | 115 | $1.1 \times 10^8$ | |
| Typical – Sweden (Ref. 18) | C | 302 | – | $9 \times 10^8$ | Minus 100μ Fraction |
| Typical – Sweden (Ref. 18) | C | 482 | – | $4 \times 10^7$ | Minus 100μ Fraction |
| Typical – Sweden (Ref. 18) | C | 302 | – | $1.1 \times 10^3$ | Plus 100μ Fraction |
| Typical – Sweden (Ref. 18) | C | 482 | – | $5 \times 10^2$ | Plus 100μ Fraction |
| U.S. – 1 (Ref. 1) | F | 400 | 97 | $1 \times 10^9$ | Minus 74μ Fraction |
| U.S. – 2 (Ref. 1) | F | 400 | 97 | $3.5 \times 10^{11}$ | Minus 74μ Fraction |
| U.S. – 3 (Ref. 1) | F | 400 | 97 | $8 \times 10^{10}$ | Minus 74μ Fraction |
| | | –––Comparison Values––– | | | |
| Tallaware, Australia (Ref. 19) | C | 392 | 122 | $7 \times 10^{12}$ | Coal |
| Pyrmount, Australia (Ref. 19) | C | 400 | – | $4 \times 10^{12}$ | Coal |
| Riverside Cement Company, California (Ref. 20) | C | 400 | 115 | $1.3 \times 10^{12}$ | Lime |
| Unknown (Ref. 20) | C | 400 | 115 | $5 \times 10^9$ | Open Hearth Fume |
| Unknown (Ref. 20) | C | 400 | 115 | $2 \times 10^{11}$ | Lead Fume |

[a] C = Collected particulate, F = Furnace emissions, A = APC inlet after water spray cooling

fabric (cotton, wool, nylon, glass, etc.), hung in frames equipped with shaking or deflation mechanisms for dust dislodgement, are the most common. In order to assure satisfactory performance and long bag life in combustion system applications, flue gas temperatures must be controlled in the range of 250-550°F (see Appendix B). The temperature range may be more narrow, depending upon the fabric and the flue gas composition.

The mechanisms of collection on fabric filters are highly complicated and include impingement, diffusion, electrostatics, and direct sieving.[21,22,23] Bag house operation reflects a compromise in economic factors as regards shaking frequency. Frequent shaking reduces bag life and particle removal efficiency (the latter as a result of the loss of the filtering action of the dust cake), but reduces the cost of fan power to overcome pressure drop. A number of studies have been conducted to evaluate this trade-off.[24]

Fabric filters are used in a number of gas-cleaning operations (particularly for the metallurgical industry), especially when very high collection efficiency is required. There is only one case recorded in the United States, however, in which a filter has been applied to the effluent from a municipal incinerator; a test installation in 1959, with a single Fiberglas bag, 11-1/2 inches in diameter and 25 feet long, operating on a side stream from the Pasadena, California, municipal incinerator.[25] There are a number of European installations now in operation. However, additional pilot testing will soon be carried out at the Greenpoint Incinerator in New York City under NAPCA sponsorship.

*(2) Concept Evaluation* Filtration[26] theory is of little use in calculating the particle-removal efficiency, as the theory deals mainly with the interaction of individual "clean" fibers with dust particles of different diameters. In contrast, the superior particle removal of the fabric filter arises, to a great extent, from the action of the entrapped filter cake. Suffice it to say that most efficiencies are in the 99%-plus range.

The usual criteria for evaluating a bag house installation are the "air-to-cloth" ratio and the maximum pressure drop. The air-to-cloth ratio is expressed as cubic feet of gas per minute per square foot of filter cloth, thus having the net dimensions of feet per minute. The pressure drop is usually expressed as inches of $H_2O$. In general industrial practice, bag house installations are designed with an air-to-cloth ratio of 1-8 feet per minute and a pressure drop of about 2-6 inches of water; the finer dusts ("fumes") require lower ratios and higher pressure drops. The filters are periodically cleaned of accumulated dust cake by shaking, bag collapse, reverse air flow, pulsed air, or reverse jet methods.

The only extensive operating experience on the use of fabric filters on U.S. incinerator effluents resulted from a series of tests, from 1959-1961, in the City of Pasadena, California. The Pasadena incinerator (now shut down) was constructed by the modification of three obsolete Sterling boilers associated with the City power plant. The pilot bag house study was conducted mainly to determine whether the plume (caused by submicron particulate) could be abated.

The Pasadena test installation operated at a ratio of about 4 feet per minute with a maximum pressure drop ranging between 4 and 6 inches of water. The measured efficiency was approximately 99.8% on an inlet loading of 0.460 grain per standard cubic foot. Over the test period, inlet temperatures varied between 300°F and 750°F with an average near 450°F. The No. 600 Menardi silicone-treated Fiberglas bag showed substantial sensitivity to operating temperature. At temperatures greater than 600°F even for short periods, the silicone coating was damaged. Although this does not itself destroy the bag, subsequent unlubricated fiber-to-fiber abrasion leads to rapid failure of the glass fabric. Temperatures above 500° caused rapid degradation of the bag and distortion of the metal frame within the bag. At temperatures greater than 400°, chemical attack, presumably by iron and by the presence of oxygen and sulfur, also shortened bag life. At temperatures near 300°F, caking occurred, leading to bag breakage on flexing.

When stable operations were established, it was determined that bag life would range between nine months and one year, providing that temperatures were maintained near 450°F. The cycle time (cleaning-to-cleaning) was 45-60 minutes. In the final stages of the experimental program, the bag house was operated on a regular basis for one year on a 24-hour day, five-days-per-week basis. Subsequently, the incinerator has been shut down, so a full-scale unit was never installed. However, the operating results were encouraging.

An interesting test program, concerned with the possible removal of sulfur trioxide ($SO_3$) from the flue gas stream, was conducted as part of the bag evaluation program. These tests showed a reduction in $SO_3$ concentration from 22.0 ppm to 0.4 ppm, in passing through the bag. Sulfur dioxide concentration remained unchanged. It is also interesting to note that these data showed approximately equal $SO_2$ and $SO_3$ concentrations in the incinerator effluent stream.

In a related situation, the Southern California Edison Company has been testing a full-scale Fiberglas bag house on a 320 MW oil-fired central station boiler (the Los Alamitos station) from 1965 to the present.[27, 28] This unit operates at a ratio of about six feet per minute and a pressure drop of six to nine inches of $H_2O$. An "alkaline additive" precoat (dolomite and limestone) is applied to adsorb most of the $SO_3$ values in the off-gas. No $SO_2$ reduction occurs.

A 33-TPD municipal incinerator in Switzerland has been equipped with bag filters, in order to eliminate fly ash emissions, which would be undesirable in view of the importance of ski-tourism in the area. The bags are also of silicone-treated glass fiber and operate at a pressure drop of 2.4-4.8 in water and an air-to-cloth ratio of 2.5 feet/min. The 2000°F furnace effluent gas is first cooled by water sprays to 1300°F and passed through a gas-to-gas heat exchanger of alloy steel, cooling the gas to 450-500°F, before introduction to the bag house. The bag house is kept hot by sealing against air inleakage, since cooling could cause condensation and corrosion. Bag life has been over two years, with no failure to date.

*(3) Conclusions* No full-scale bag house units now exist on municipal incinerators in the United States, although several installations are in operation in Europe. There may be sufficient information available to allow the design of such units for municipal incinerators, but if so, the information is proprietary at this time. Pilot plant experience is required to enable optimization of such a unit, as filtration theory is of little design importance in comparison with the practical problems of filtering a particular dust from a particular gas.

It is clear, however, that from the standpoint of particulate removal efficiency, the fabric filter will surpass all other APC systems. Important practical problems include:

- The introduction of tar materials in the condensed phase (either as droplets or carried-on particulate) can cause sticking of the cake and subsequent blinding of the filter fabric. This would either cause high pressure drop (increased power cost) or require frequent bag replacement or maintenance.

- Sensitivity of most commonly used commercial bag materials to high temperatures demands reliable, fast-acting flue gas tempering equipment. Emergency by-pass flues would also be desirable.

- Flue gas and particulate entering a bag house should be without free moisture (entrained droplets or moist fly ash). This requirement reflects on the need for sufficient residence time for evaporation, following water spray gas cooling.

## e. Scrubbers

*(1) Introduction* There are many types of devices for contacting liquids with gas streams for the purpose of removing particulate matter and gaseous pollutants. Three approaches will be considered in connection with incinerators:

- Wetted surfaces, i.e., systems of wetted pipes, baffles or walls located in the off-gas duct;
- Devices for contacting the gas with a liquid spray, either in a spray-filled chamber or in a Venturi; and
- Devices for bubbling the gas through a quantity of liquid (by ducting it below a liquid surface or by blowing it through impingement trays or through a packed column).

Only the first two of these approaches have been used to any significant extent on municipal incinerators, although a few impingement-plate scrubbers have been installed. All these devices have in common the fact that they humidify and cool the gas, and therefore, produce a "steam" plume at the stack under some atmospheric conditions (see Appendix B). They also share the characteristic that, for a given dust, the application of more power per unit of gas fed (greater pressure drop) generally results in a higher degree of particulate removal.

### (2) Concept Evaluation

*(a) Wetted Surfaces* Many incinerators have wetted "obstacles" placed in the off-gas ducting. If these baffles are kept wet at all times, they can be made of metal. Because of corrosion problems, however, refractory construction is usually preferred. These are relatively low-pressure devices (0.1-1 in. of water), and, as such, their particulate removal efficiencies are low; but higher than those of dry or wet bottom settling chambers.

In approaching the predication of baffle efficiency from first principles, the target efficiency is estimated for a given particle-size on a given baffle diameter. Target efficiency is defined as the fraction of particles of a given size in the volume swept out by the surface, which strikes the collecting surface.[26] Standard impingement relationships, such as that in Figure VII-6, are often used to correlate target efficiency with the dimensionless group $D_p^2(\rho_s-\rho_g)v_o/18\mu D_b$, known as the Separation Number, where:

$D_p$ = particle diameter, ft;
$D_b$ = baffle diameter, ft;
$v_o$ = approach velocity of gas stream; ft/sec;
$\mu$ = gas viscosity, lb/ft-sec;
$\rho_s$ = solid density, lb/cu ft; and
$\rho_g$ = gas density, lb/cu ft.

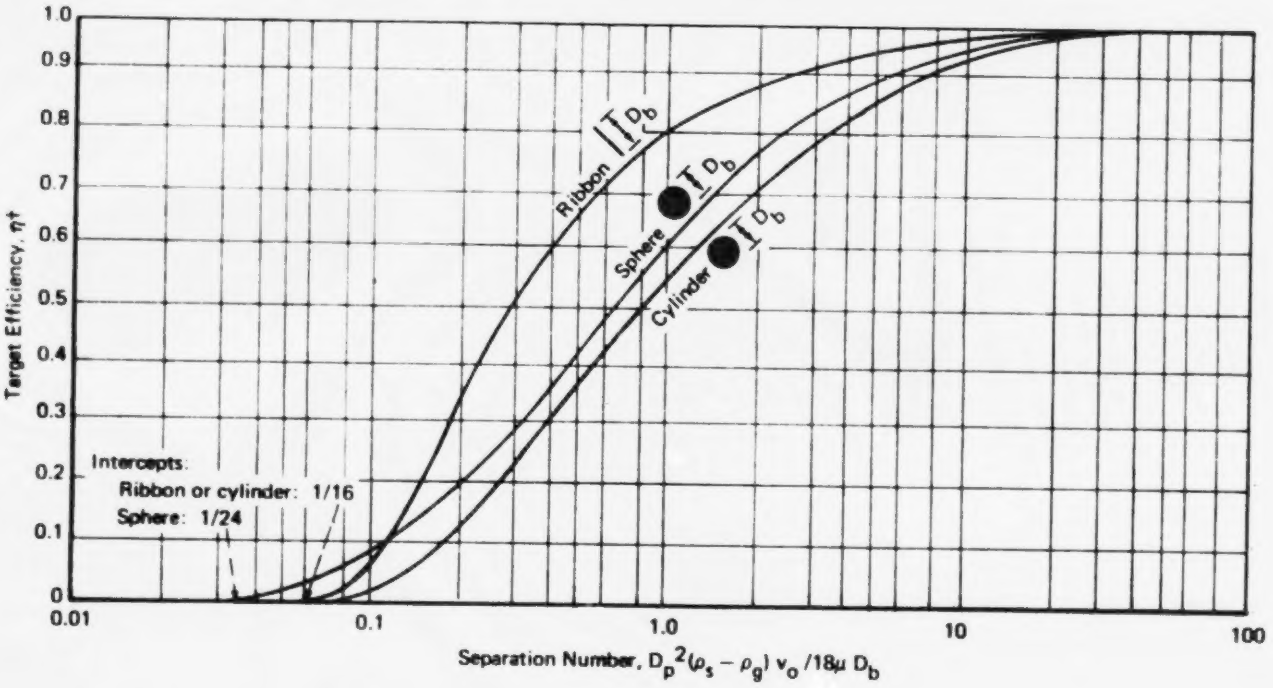


FIGURE VII–6 TARGET EFFICIENCY OF SPHERES, CYLINDERS, AND RIBBONS[26]

Consideration of the inertial impaction data of Figure VII-6 shows that particles finer than that given by the relationship:

$$d = 0.25 \left[ \frac{18\mu D}{(\rho_s - \rho_g)\, v_o} \right]^{1/2} \qquad (10)$$

will not be trapped on a perpendicular flat baffle, where:

$d$ = smallest diameter particle to impact on a target, ft;

$D$ = width of a flat plate target, ft;

$v_o$ = approach velocity of gas stream, ft/sec;

$\mu$ = gas viscosity, lb/ft-sec;

$\rho_s$ = solid density, lb/cu ft; and

$\rho_g$ = gas density, lb/cu ft.

One simple approach to estimating performance is calculating the fraction of the particulate which is potentially collectible, using Equation (10) to calculate the cut-off diameter. Then one can assume removal of a fraction of the collectible particulates corresponding to the fraction of cross section masked by the projected area of the obstacles; compounding these if several groups of obstacles are installed.

For example, the circular furnace of Plant No. 20 (Table J-1, Appendix J), has three closely-spaced rows of spray-wetted brick 90° triangles (each having an 18-in. outside dimension on each leg, and a 25.5-in. frontal dimension). The first row reaches the full height of the 20-ft high by 12-ft wide chamber while the second and third rows rise to a 16.25-ft row of tie-bricks. Application of Equation (10) to the approach velocity of 9.4 ft/sec for, say, air at 1500°F, leads to a minimum particle size of about 65 microns trapped on the (equivalent) 25.5-in. wide baffle. Since we have no particle-size distribution data for this unit, let us assume our nominal distribution (see U.S.A. No. 2 – pg. VII-14). For that dust, a cut at 65 microns would mean that only 51% of the dust is potentially collectible. In the configuration described, there are four 6.5-in. spacings across the first row and eight 4.5-in. spacings across the second and third rows. This corresponds to 18% and 25% open area, respectively. Thus, one could estimate, for the first row, a maximum removal efficiency of [1-0.18] [51%] or 42%. Gas acceleration and cooling (i.e., to 600° at the scrubber exit) in the second and third rows would give a maximum gas velocity (i.e., leaving the first row at 1060°F) of 42 ft/sec, dropping the minimum collected particle diameter to 30 microns (60% of the total particulate). This increases the maximum overall efficiency to about [1-0.18] [51%] + [1-0.25] [60%-42%] = 55.5%; the term (60%-42%) reflecting the efficiency increment added by the increased approach velocity. This calculation method is, however, quite simplified. In 1966, an efficiency of 63.6% was measured on this scrubber device.

A value of 53% was measured for the wetted baffles of Installation No. 2 of Walker and Schmitz,[1] who also measured only a 10% efficiency (an unreasonably low value), for the wetted baffle of their Installation No. 3. A series of closely-spaced, wetted impact collection baffles at Plant No. 6 (see Table VI-1), installed after a spray chamber and above the wet pond floor just before the stack, showed an average efficiency of 89.1% in 1961; an improbably high result.

The pressure drop across such a row of obstacles can be computed as the drop across an orifice of equivalent free area. If there are "n" such rows in a bank, the total pressure drop is more than that for one row, but less than n times this number, because the rows are presumably close enough, so that there is not space for full gas deceleration between rows. Thus, for Plant No. 20, if the gas velocity is about 9.4 ft/sec at 1500°F, the initial orifices have 18% free duct area (with an orifice coefficient of 0.62), the series of enlargements and contractions with cooling are calculated to cause a pressure drop of about 0.6 in. of water. A drop of 0.84 in. of water has been measured.

*(b) Devices for Scrubbing Gas Bubbles* Devices in which the gas is passed through one or more impingement trays are of increasing importance. Such trays contain several hundred to several thousand orifices, with a sheet-metal baffle located directly above each hole. The baffles are submerged in the scrubbing liquid and the gas impinges directly on the wet baffles. The pressure drop is normally about 4 in. of water per tray. Although only one tray is used in most incinerator installations, the trend in such applications is to use two or more trays.

Published data on the efficiency of these units on incinerator effluent are scarce. If one applies the efficiency curve of Stairmand,[29] given in Figure VII-7, to the nominal dust particle-size distribution selected above, an efficiency of 92.5% can be predicted for a single tray. A test of such an impingement scrubber (56,000 scfm) was made in 1959 on the Pasadena, California municipal incinerator, where it yielded a result of 89.5%. There are no other available test data showing the efficiency of such units; outlet dust loadings have been reported, but without the corresponding inlet loadings.

Devices involving the bubbling of the gas through a thin blanket of liquid involve a somewhat lower pressure drop than for the impingement tray; thus their efficiency can be expected to be about midway between that of the "wetted surface" type described in the preceding section, and that of the impingement tray type described above. A recent test on a mid-range (1-4 in. of water) pressure drop version of such a system showed an efficiency of 79.4%. Insufficient detailed test data are available, however, to attempt to check this performance with the predictive equations.

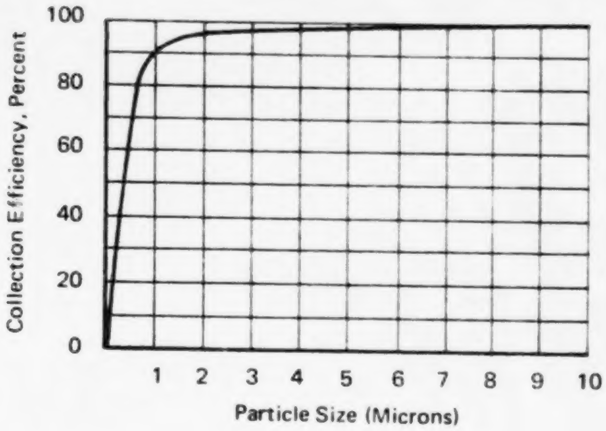


**FIGURE VII–7** **GRADE-EFFICIENCY CURVE FOR WET-IMPINGEMENT SCRUBBER EFFICIENCY AT 5μ - 97%; PARTICLE DENSITY = 2.5**[29]

Data for packed columns on incinerator effluent are not available. In the two instances where these have been installed, the pressure drop was comparable to that of a single-impingement plate (around 4-5 in. of water); thus the efficiency should be comparable. In incinerator pilot tests of one unit containing a wetted porous element, a pressure drop of 7 in. of $H_2O$ produced a particle removal of 87.5%, somewhat lower than expected on the basis of the results for impingement trays (at 4 in. of $H_2O$) described above.

*(c) Devices for Spraying the Gas* The low-pressure-drop devices by which a low-pressure spray is directed into the gas have efficiencies comparable with those of the wetted-surface devices mentioned above. On the other hand, high-energy Venturi scrubbers offer an increase in efficiency beyond that of an impingement-plate device.

In a Venturi scrubber, the gas is accelerated through a venturi restriction producing a fine spray from a liquid stream injected into the venturi "throat." Impaction of the dust on these spray particles provides the means to collect the particulate. Although pilot tests have been run with venturi units, and a full-scale device (by Chemico) has been installed at the 73rd Street Incinerator in New York, no performance data are yet available. In order to estimate what could be expected of such devices at various pressure drops, however, we can assume the nominal dust size distribution (see U.S.A. No. 2 – pg. VII-14) and apply the method of Calvert.[30] Given the water usage (typically about 10 gallons per 1000 cubic feet of gas). Figure VII-8, adapted from Calvert's Figure 13, can be used to estimate the gas velocity for various pressure drops. Strictly, this graphical relationship only holds near ambient temperatures, but rapid gas cooling (by water evaporation) in the venturi approaches these conditions. The average liquid particle diameter for two-fluid atomization can then be estimated from:

$$d_o = \frac{16400}{V_g} + 1.45\,(L')^{1.5} \qquad (11)$$

where:

$d_o$ = average liquid drop diameter in spray, microns
$V_g$ = gas velocity in throat, ft/sec
$L'$ = liquid usage, gal/1000 cu ft

Next, a spray Reynolds number is calculated as

$$Re = \frac{d_o V_g \rho_g (3.28 \times 10^{-6})}{\mu_g} \qquad (12)$$

where, in addition to the preceding definition:

$Re$ = Reynolds number, dimensionless
$\rho_g$ = gas density, lb/cu ft
$\mu_g$ = gas viscosity, lb/ft-sec

The stopping distance, $z'$, in numbers of drop diameters (as $z'/d_o$), is calculated next, as

$$z'/d_o = 8.16\,(Re) \qquad (13)$$

where the stopping distance is the distance traveled by the water droplet before it attains gas velocity.

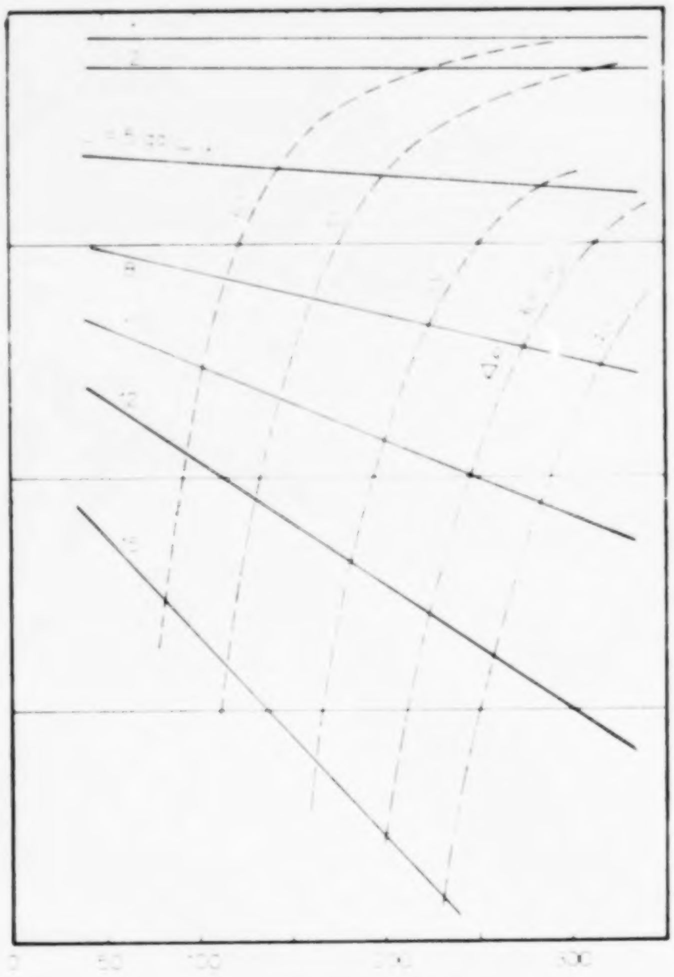


FIGURE VII–8 GENERAL RELATIONSHIP BETWEEN LIQUID RATE, PRESSURE DROP, AND GAS VELOCITY FOR VENTURI SCRUBBERS (60°F, 1 atm)[31]

This enables us to use Figure VII-9, adapted from Calvert's Figure 12,[32] to obtain the particle collection efficiency for any particular solid particle size. In using this plot, the particle radius $d_\mu$ must be corrected to its effective aerodynamic value $d'_\mu$:

$$d'_\mu = d_\mu \sqrt{\rho'_s / 1.0} \qquad (14)$$

where

$d_\mu$ = dust particle diameter, microns

$d'_\mu$ = effective aerodynamic dust particle diameter, microns

$\rho'_s$ = particle density, g/cu cm

Application of these relationships and procedures to the nominal dust size distribution leads to the results in Table VII-15.

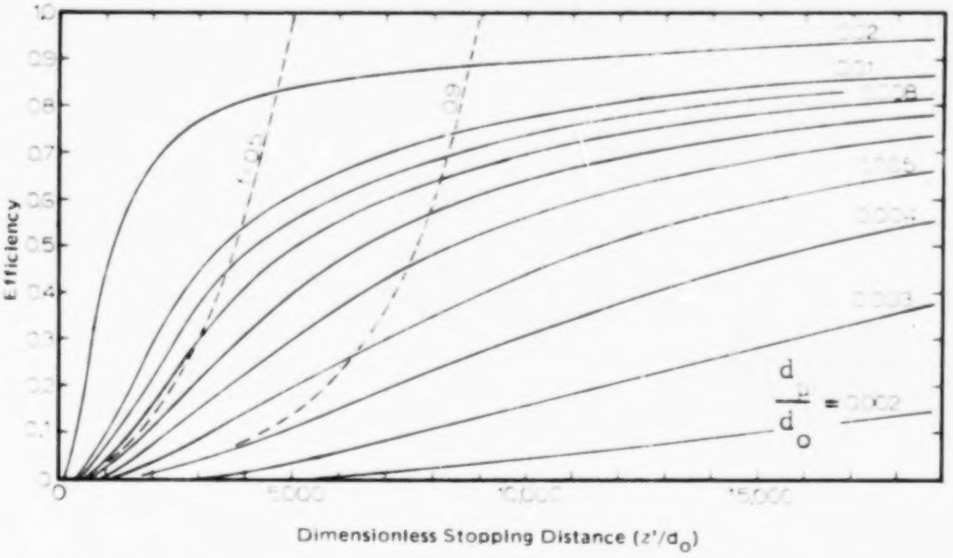


FIGURE VII–9 THEORETICAL PARTICLE COLLECTION EFFICIENCY VS. DIMENSIONLESS DROP STOPPING DISTANCE WITH PARTICLE-TO-DROP SIZE RATIO AS PARAMETER[32]

$$\left(\frac{z'}{d_o} = \frac{\text{stopping distance}}{\text{drop diameter}}\right)$$

*(3) Conclusions* There is adequate technology available to allow rational design evaluation and selection of scrubber units for particulate removal from municipal incinerator effluent. Wetted baffle installations, however, are sufficiently low in efficiency and variable in design, suffering from many of the same design disadvantages mentioned above for settling chambers.

Current trends in incinerator design show that wet scrubbing systems will play an important part in incinerator APC in the future. Based on the theoretical evaluations above and the limited test data available, we conclude that scrubbers can be effective in reducing particulate air pollution, especially if combined with improved operating procedures to minimize the formation of the very fine carbon particles within the furnace.

The operation of wet scrubbers in the past has not been without its problems. Foremost among these are:

- Corrosion;
- Plume Formation;
- High Cost;
- High Pressure Drop
- Ash Slurry Handling; and
- Ash Slurry Disposal.

## TABLE VII-15

## CALCULATED VENTURI SCRUBBER PERFORMANCE ON NOMINAL DUST SIZE DISTRIBUTION

| | Pounds of Leaving Dust per 100 Pounds of Total Entering Dust | | | |
|---|---|---|---|---|
| | | At Outlet | | |
| Size Range | At Inlet | P = 5"$H_2O$ | P = 15"$H_2O$ | P = 25"$H_2O$ |
| < .1-μ | 2 lb. | 2.0 lb. | 2.0 lb. | 2.0 lb. |
| .1- .5 | 5 | 5.0 | 4.6 | 4.4 |
| .5- 1.0 | 2 | 1.4 | 0.5 | 0.2 |
| 1.0- 2.0 | 5 | 0.9 | 0.4 | 0.2 |
| 2.0- 5.0 | 7 | 0.3 | 0.1 | 0.1 |
| 5.0-10.0 | 6 | 0.2 | 0.1 | 0.1 |
| >10.0 | 73 | 0.0 | 0.0 | 0.0 |
| | 100 lb. | 9.8 lb. | 7.7 lb. | 7.0 lb. |
| Calculated Efficiency: | | 90.2% | 92.3% | 93.0% |

The gases from incinerators contain small but significant amounts of acidic gases, predominantly hydrogen chloride and sulfur dioxide. These mineral acids, in combination with organic acids formed by incomplete combustion of hydrocarbons, can rapidly drop the pH of recirculated scrubber water to low values (1.5-2.5 is not unusual). The combination of low pH and chloride ion has been clearly shown responsible for rapid wastage of mild steels and catastrophic failure of stainless steels. Although treatment with alkali (such as soda ash) is helpful in reducing the acidity, the chloride ion remains active. As a result, use of acid-resistant refractory and cautious selection of alloys for exposed metal application is necessary for long equipment life. The problems described above are mitigated to a great extent by once-through water use (rather than recirculated) and by use of pumps and piping of nonmetals or with nonmetal linings. The cost, however, is not low.

The problem of plume formation is discussed in some detail in Appendix B. Although it is not an air pollution problem, the public is infrequently aware that the heavy plume (often quite dark under certain lighting conditions) is a sign of progress in air pollution abatement. In most cases, however, the plume is an unavoidable consequence of scrubber operation.

The problem of high cost applies more to the high-energy scrubbers than to the wetted baffle type. The costs reflect heavily upon the high pressure drop (fan power) for the former types which, as suggested above, is the price of efficiency. The pressure drops of the wet baffle systems, while not excessive, may place an unacceptable burden on natural stack draft, in addition to the decreased stack temperatures. Several plants which have added wet scrubbers have found that induced draft fans were also necessary.

Ash slurry handling and disposal are other problems which often occur with wet collection systems. In addition to the corrosive nature indicated above, fly ash slurries are extremely abrasive. Erosive attack of pipes (particularly at turns), pump impellers, and cyclone separators are common. Special materials (such as fiberglass reenforced polyester), special piping arrangements, regular inspection, and maintenance have been helpful in minimizing the severity of these problems.

In plants with recirculated scrubber water, continuous particulate removal is necessary. Although clarifiers, cyclones and similar equipment substantially improve water quality, the resulting fluid can be troublesome, due to encrustations in pipes and other flow equipment, and plugging of spray nozzles. In most cases, a substantial purge stream is required. Fresh water is needed for fine spray nozzle applications.

The problems of slurry disposal reflect the water pollution potential (BOD, COD, pH, dissolved and suspended solids) of fly ash slurries and/or the limitations which may be placed on the quality of waters serviced to the city sewer system. Although treatment is possible with existing technology, the cost and/or land requirements may be excessive for many urban plants.

### 5. Removal of Gaseous Pollutants

#### a. Introduction

The gaseous pollutants in Table VII-6 can be expected to pass unchanged through the dry control devices discussed in the previous section, with the exception that bag filter collecting devices have been claimed to be capable of absorbing over 90% of the $H_2SO_4$ (or $SO_3$) values[33] and some of the $SO_2$.[34] when coated with alkaline additives, such as limestone and dolomite. (Claims of over 90% $SO_3$ removal on bag filters have also been made even when no additive was used.[35]) The wet control devices described in the preceding section can be expected to remove several of the gaseous pollutants, even though their prime purpose and greatest effectiveness is the removal of particulates.

b. Concept Evaluation

Wet scrubbers (wet baffles, wet cyclones, and scrubbers) are, in general, less effective than a single equilibrium contact (theoretical stage) and so we can compute their maximum performance on this basis. (Indeed, since most are co-current flow devices, they can at best only approach one theoretical stage in performance.)

Consider a theoretical stage as shown in Figure VII-10, in which L lb mols of liquid flow through for every cubic foot of gas. The liquid leaving such a unit is in equilibrium with the vapor leaving it. Ignoring the mass changes of the streams, by assuming the amount of material absorbed in this contactor, is negligible with respect to the mass of either the gas or liquid stream, for any component:

Mols leaving gas = mols entering liquid

$$\frac{(P_{in} - P_{out})}{RT} = L\,(x_{out} - x_{in}) \tag{15}$$

where

$P_{in}$ = partial pressure of component in gas at inlet, atm

$P_{out}$ = partial pressure of component in gas at outlet, atm

L = liquid rate, lb mol liquid/cubic foot gas

R = universal gas constant (0.7302 atm-ft$^3$/lb mol-°R)

T = temperature of stage, °Rankine

$x_{in}$ = concentration of component in liquid at inlet, mol fraction

$x_{out}$ = concentration of component in liquid at outlet, mol fraction

If we can assume Henry's Law applies to the solubility of the component, then

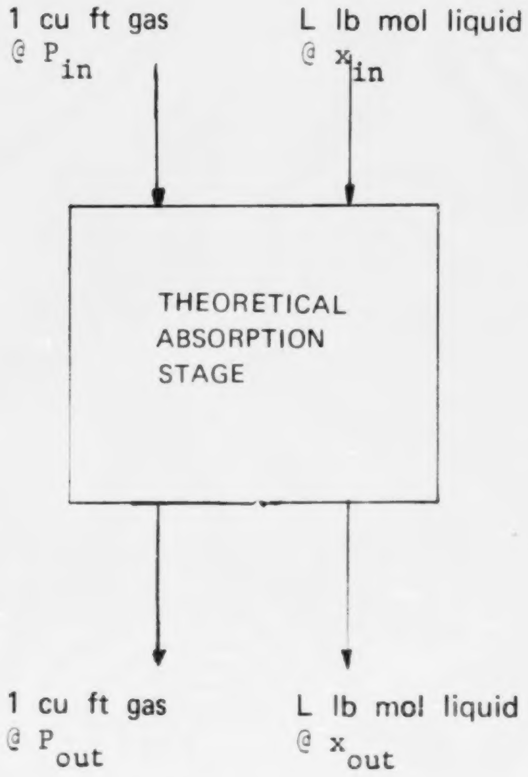
$$P_{out} = Hx_{out} \tag{16}$$

where

H = Henry's Law constant, atm/mol fraction

FIGURE VII–10

SCHEMATIC REPRESENTATION OF A THEORETICAL ABSORPTION STAGE


1 cu ft gas
@ $P_{in}$
L lb mol liquid
@ $x_{in}$
THEORETICAL
ABSORPTION
STAGE
1 cu ft gas
@ $P_{out}$
L lb mol liquid
@ $x_{out}$

Substituting, and assuming no pollutant in the entering liquid stream ($x_{in} = 0$), we obtain:

$$\frac{P_{out}}{P_{in}} = \frac{H}{LRT + H} \tag{17}$$

and thus the maximum efficiency of absorption is:

$$\text{Efficiency} = 1 - \frac{P_{out}}{P_{in}} = \frac{LRT}{LRT + H} \tag{18}$$

Efficiency is favored by high values of L and low values of H: high liquor rates and high solubilities. The maximum single-stage removal efficiencies calculated using Equation (18) are shown in Table VII-16 for the gaseous components of Table VII-6, for a nominal water rate of 10 gal/1000 cu ft of gas. The removal efficiencies are seen to be negligible (i.e., below 25%) at 70°C for all except the acid components of HCl, HF and acetic acid. If $H_2SO_4$ or $SO_3$ is present, it can also be assumed to be removed if an acid mist (very small particles) is not formed. $NO_2$ can also be assumed to be absorbed: $H_2O + 2HNO_3 + NO$. Note, however, that one-third of the $NO_2$ is released as NO which can subsequently oxidize to $NO_2$.

The above removal efficiencies can be applied to the nominal gas composition of Table VII-6 to determine the maximum lowering of the scrubber water's pH, for comparison with practical experience. The calculation is performed in Table VII-17, which shows a final pH of about 2.2 for the complete (equilibrium) scrubbing of one theoretical stage (at 10 gal/Mcf water rate). For comparison, at Plant No. 104 (Table J-1, Appendix J), the water enters at pH 6.7 and leaves at pH 5.0. At a southwestern plant, the treated make-up enters at a pH of 8.1 and leaves at a value of from 3.6 to 6.0. Typical pH values for effluent liquid seldom approach the region of 2.5. Although the water feed rates and evaporation rates are not known for these plants, if one assumes the net flows to range about the "typical value" of 10 gal/Mcf, it would appear that scrubbers on operating plants do not approach the gas scrubbing efficiency of one theoretical stage. The alkaline nature of the collected ash, however, in addition to the uncertainty in water flow rates, makes this conclusion very tentative.

The lowering of pH value from the nominal value of 7.0 for pure water further decreases the already-small absorption efficiencies shown in Table VII-16 for most gaseous components. If the water is reused, the acidity may rise still further, decreasing solubilities yet again. It has been noted, however, that after some time has passed (as in a clarifier) the slowly dissolving alkaline fly ash tends to increase the pH, thus increasing acid gas solubility.

## TABLE VII-16

## MAXIMUM ABSORPTION EFFICIENCY FOR SINGLE EQUILIBRIUM CONTACT STAGE[a]

| Component | Henry's Law Constant 30°C(86°F) | Henry's Law Constant 70°C(158°F) | Maximum Absorption Efficiency 30°C(86°F) | Maximum Absorption Efficiency 70°C(158°F) |
|---|---|---|---|---|
| CO | $6.2 \times 10^4$ (atm/mol fraction) | $9.8 \times 10^4$ (atm/mol fraction) | 0.003% | 0.002% |
| NO | $3.1 \times 10^4$ | $4.4 \times 10^4$ | 0.006 | 0.005 |
| $CH_4$ | $3.0 \times 10^4$ | $1.0 \times 10^5$ | 0.006 | 0.002 |
| $CO_2$ | $1.8 \times 10^3$ | $3.9 \times 10^3$ | 0.10 | 0.05 |
| $SO_2$ | $1.6 \times 10^1$ | $1.3 \times 10^2$ | 10.3 | 1.6 |
| HCHO (formaldehyde) | $1.2 \times 10^1$ | $1.4 \times 10^2$ | 13.3 | 1.5 |
| $CH_3COOH$ (acetic acid) | $2.7 \times 10^{-2}$ | $1.8 \times 10^{-1}$ | 99.0 | 92.0 |
| HF | $3.0 \times 10^{-3}$ | $5.5 \times 10^{-2}$ | 100.0 | 97.0 |
| HC1 | $2.0 \times 10^{-5}$ | $1.3 \times 10^{-3}$ | 100.0 | 100.0 |

---

[a] Assuming only trace quantities being absorbed in water, and using 10 gallons per 1000 cubic feet of gas.

## TABLE VII-17

### CALCULATION OF SCRUBBER WATER EXIT ACIDITY FROM ONE THEORETICAL STAGE

Basis: 1000 cu ft gas; 10 gal liquid $H_2O$/1000 cu ft gas; 70°C

| Component | Amount at Gas Inlet, cu ft (Table VII-6) | Maximum Possible Removal Efficiency, % (Table VII-16) | Amount Removed moles x $10^6$ |
|---|---|---|---|
| CO | 1.5 | 0.002 | 0.067 |
| * $NO_2$ | 0.015 | (100.) | 33.256 |
| NO | 0.035 | 0.005 | 0.388 |
| $CH_4$ | 0.100 | 0.002 | 0.004 |
| * $CH_3COOH$ | 0.001 | 92.0 | 2.040 |
| HCHO | 0.003 | 1.5 | 0.100 |
| * $SO_2$ | 0.030 | 1.6 | 1.064 |
| * $H_2SO_4$ | 0.050 | (100.) | 110.852 |
| * HCl | 0.060 | 100. | 133.023 |
| * HF | 0.001 | 97. | 2.151 |
| * $CO_2$ | 45. | 0.05 | 49.883 |
| | | Total | 332.828 |

---

If each acid-forming component (marked with an asterisk) is assumed to be fully ionized in the water solution (noting $NO_2$ only yields 2/3 of its H+), 482 x $10^{-6}$ moles of H+ are released, equivalent to 5.8 x $10^{-3}$ gm-moles/liter or pH 2.24.

### c. Conclusions

A simple analysis based on a single gas-liquid equilibrium contact can be performed, to determine which incinerator off-gases can be removed in wet devices. From this analysis, it can be seen that particulate scrubbers can be expected to remove (in addition to solids) a portion of the $H_2SO_4$, HCl, $SO_3$ HF, organic acids, and $NO_2$; the other components – CO, $CO_2$, NO, hydrocarbons, aldehydes, and $SO_2$ – will be essentially untouched by water scrubbing. In practice, most of these devices may not be achieving even the contacting equivalent of one theoretical stage as discussed in Section V-G.

In some cases (the polynuclear hydrocarbons and other heavy tars), the gas cooling which occurs in wet scrubbers may lead to condensation: either self-nucleated or upon existing particulate. As a result, higher removal efficiencies may be realized. For example, a water spray scrubber was shown to have 96.9% efficiency in the removal of polynuclear hydrocarbons from a 50 TPD multiple-chamber incinerator.[75] Although this value appears high, it suggests the importance of mechanisms other than simple gas-liquid absorption. Similarly, $SO_3$ may not be absorbed due to formation of a sulfuric acid aerosol.

In data from Plant No. 20 (Table J-1, Appendix J), the change in $SO_x$ concentration in passing through a series of three water spray wetted refractory baffles (pressure drop = 0.84" w.g.) appears small (Table VII-18). Nitrogen oxide reduction efficiency, however, averaged 68%. The high efficiency for $NO_x$ reduction appears high in comparison to other combustion system wet scrubber performance data.

Data on a venturi scrubber[36] operating with 2-10 gal/Mcf water rate between 22 and 40 inches pressure drop ranged in $SO_2$ removal efficiency between 82% and 95% on an inlet concentration of 2.2 ppm. Since this unit is operated co-currently, it is apparent that other processes are occurring to give the effect of several counter-current stages. At the operating temperature of 70°F and at an assumed liquid rate of ten gal/Mcf, the one-stage maximum efficiency would be 13.3%.

Based on these limited data, it would appear that simple low-energy co-current scrubbers operate at gaseous pollutant removal levels somewhat less than at a theoretical stage. High energy, complex systems may improve substantially upon this efficiency. Additional data and analysis are required in order to determine these values.

It is apparent that some collection of gaseous pollutants does occur, however, as evidenced by the low pH of scrubber water.

## TABLE VII-18

## DATA FROM WETTED BAFFLE ABSORPTION TEST
(Recirculated Water – Average pH = 3.09)

| | Test 1 | Test 2 | Test 3 |
|---|---|---|---|
| I. $SO_x$ Concentration (as $SO_2$) | | | |
| Scrubber Inlet | 28.6 ppm | 62.8 ppm | 19.7 ppm |
| Scrubber Outlet* | 27.1 ppm | 75.6 ppm | 22.4 ppm |
| Removal Efficiency | 5.2% | – | – |
| II. $NO_x$ Concentration (as $NO_2$) | | | |
| Scrubber Inlet | 125.0 ppm | 104 ppm | 112 ppm |
| Scrubber Outlet* | 45.8 ppm | 33.2 ppm | 28.5 ppm |
| Removal Efficiency | 63% | 68% | 74% |

* roughly corrected for dilution

### 6. The Economics of Incinerator Air Pollution Control

Air pollution control systems investment and total operating cost analyses were made for devices whose performance and applicability were evaluated above for incinerator applications. The systems were:

| | Average Particulate Remove Efficiency (percent) |
|---|---|
| • Wet settling chambers | 40 |
| • Medium- and high–efficiency cyclones | 68 and 83 |
| • Low- and medium–energy scrubbers | 91 and 93 |
| • Electrostatic precipitators designed for 95% and 99% efficiency | 95 and 99 |
| • Fabric filters | 99.5 |

The costs shown below were developed on the basis of an extensive review of recent manufacturers' quotes, review of actual plant cost data, information available through experience in the field, and recent data presented in the literature, including those presented by NAPCA.[38] The costs for the various systems were developed in a consistent manner to illustrate the relative costs among the various control systems. As in any such general comparison, costs for actual incinerator installations may vary by about ± 20% from the curves presented. In addition to the investment cost shown, appropriate demolition costs and salvage credits must be added when considering additions to existing plants. As a *rough* estimate, this could approximate 5-10% of the costs shown for new equipment of the same type.

a. Capital Investment (Basis – 1969 dollars, Boston, Mass. Location)

The installed investment costs for the various systems are given in Figure VII-11 as a function of capacity in $/cfm. The relationship between $/cfm and $/TPD depends upon the excess air level characteristic of the specific furnace. For furnaces operating at 150% excess air (at the APC system) with evaporative

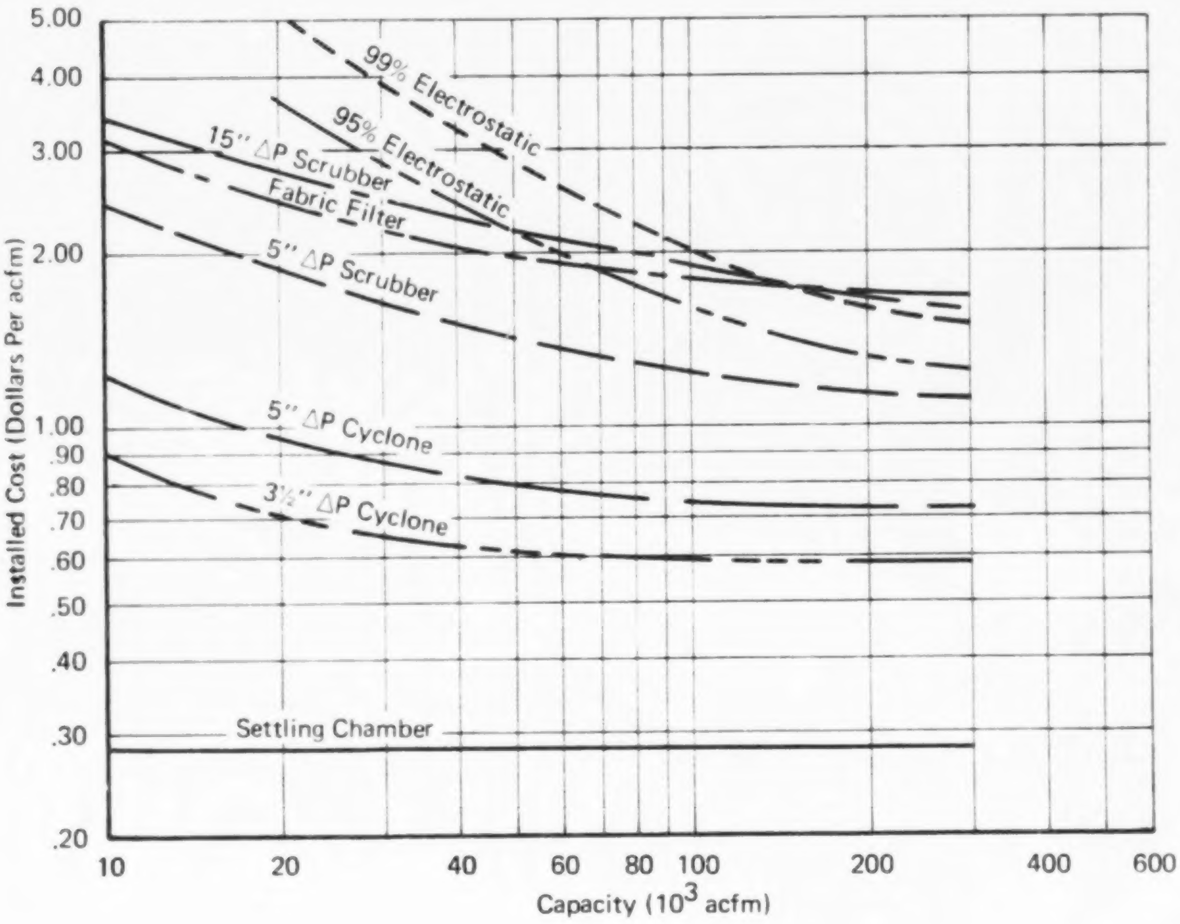


FIGURE VII–11 AIR POLLUTION CONTROL SYSTEMS – TOTAL INSTALLED COSTS

cooling, a conversion factor of 450 can be used (see Table B-1, Appendix B, for other conditions). The costs include all auxiliaries, fans, motors, ducting, etc., completely installed. The systems are treated generically, rather than dealing with particular brands or design, and are differentiated by the pertinent system design parameter (pressure drop or design efficiency). With the exception of the settling chamber (which treats gases directly from the incinerator), all system costs are based on gas feed at a temperature of 500°F. Standard steel construction was used in all dry systems and stainless steel (316 L) in wet systems. In adding these systems to existing plants, flue gas conditioning to 500°F may be required. The investment and operating costs for flue gas conditioning systems are presented in Appendix B.

b. Annual Operating Costs

Annual costs for operation of the systems, including debt retirement and interest are given in Figures VII-12, VII-13, and VII-14 for 1, 2, and 3 shifts per day of operation, respectively. Annual operating costs were calculated, following discussions with vendors, review of the literature, and analysis of plant data:

- Capital Charges as a Function of Installed Cost

  Amortization – 6.67%/year (15-year life)
  Interest – 3.14%/year (6% bonds retired over 20 years)

- Utility Costs

  Electricity – 1.5¢/kilowatt-hour
  Water – 30¢/1000 gallons (includes sewer charges)

No solid or liquid waste disposal costs are included. The operating costs for specific APC systems were estimated:

- Settling Chamber

  Essentially no operating costs in addition to capital charges.

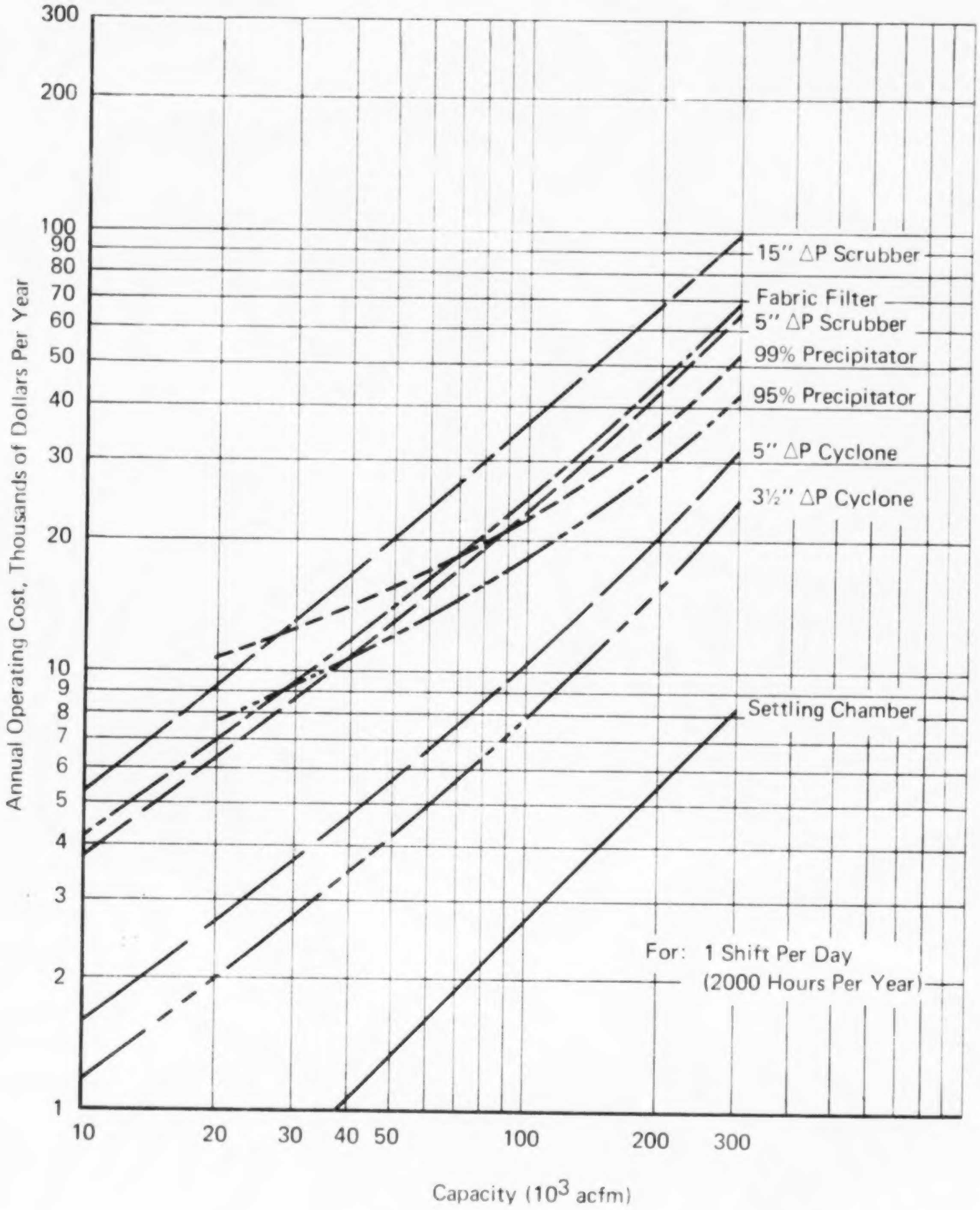


FIGURE VII–12 AIR POLLUTION CONTROL SYSTEMS ANNUAL OPERATING COSTS

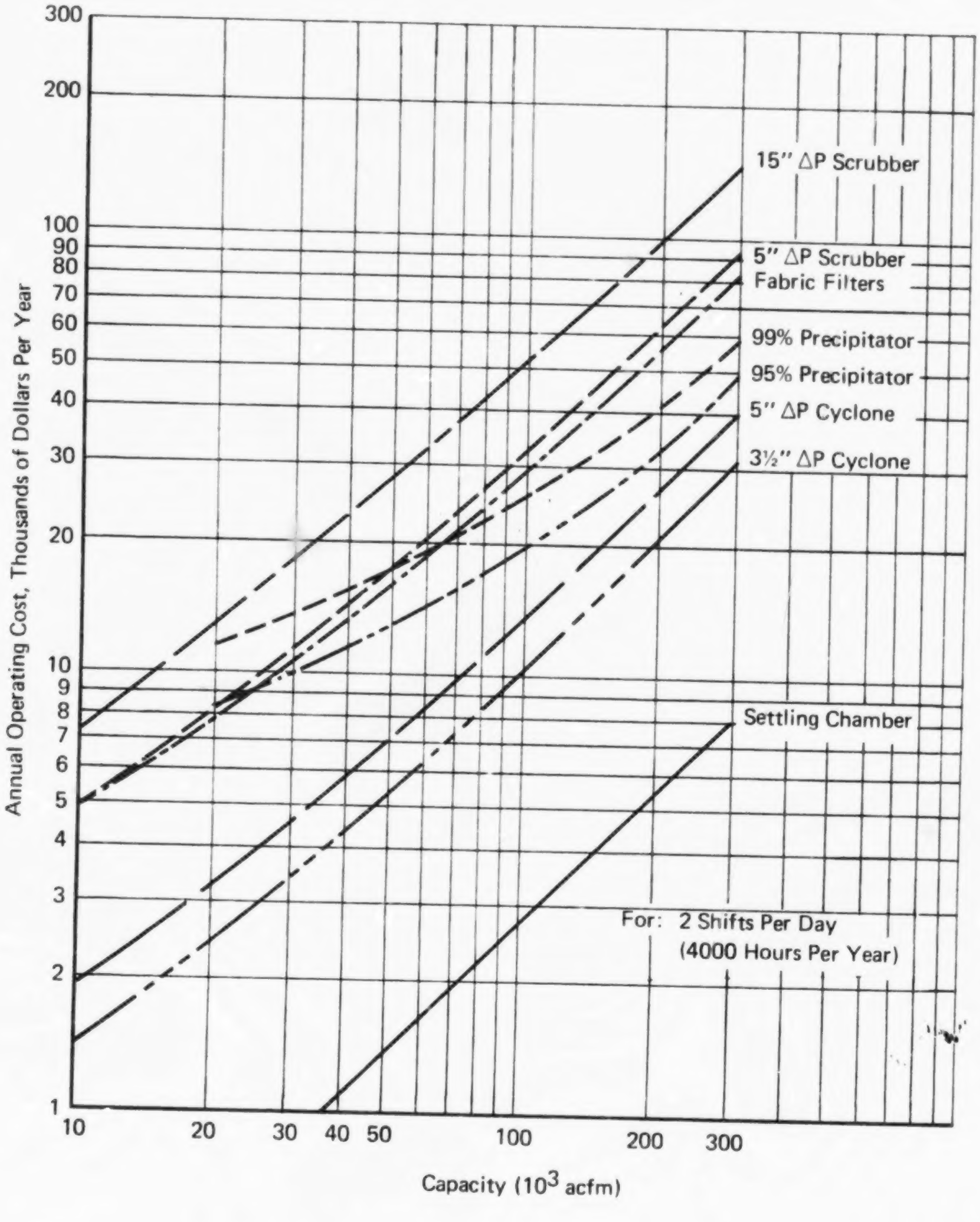


FIGURE VII–13 AIR POLLUTION CONTROL SYSTEMS ANNUAL OPERATING COSTS

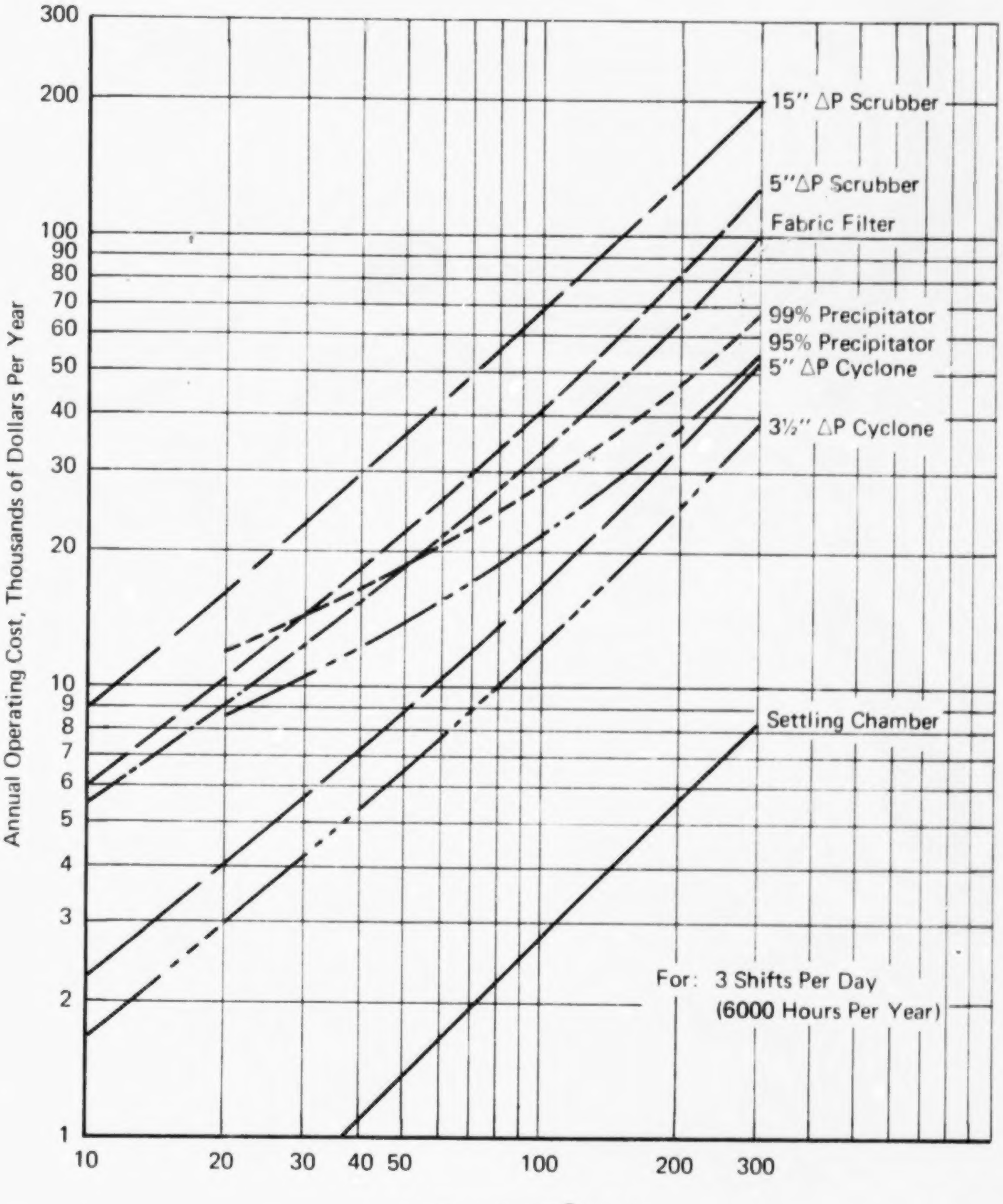


FIGURE VII–14 AIR POLLUTION CONTROL SYSTEMS ANNUAL OPERATING COSTS

- Cyclones

pressure drop — 3-1/2 inches of water — large-diameter cyclone
— 5 inches of water — multiple cyclone
maintenance — 2% of installed cost/year

- Scrubbers

pressure drop — 5 inches of water — low-energy scrubber
— 15 inches of water — medium-energy scrubber
water — evaporation — 0.5 gal/1000 acf treated gas
scrubbing rate — 10 gal/1000 acf treated gas
recycle to purge rate — 10:1
maintenance — including water treatment — 4% of installed cost/year

- Electrostatic Precipitators

pressure drop — 1 inch water
precipitator power — 0.0005 kw/cfm — 99% efficiency
— 0.00035 kw/cfm — 95% efficiency
maintenance — 1% of installed cost/year

- Fabric Filters

pressure drop — 4 inches of water
maintenance, including bag replacement — 6% of installed cost/year

The maintenance costs given above are for three shifts per day or 6000 hours per year of operation. For lower usage levels, annual maintenance costs are reduced:

2 shifts/day — 80% of 3-shift/day cost
1 shift/day — 50% of 3-shift/day cost

Table VII-19 presents, for each control system, the relative contribution of capital charges, maintenance, power, and water to the annual operating costs for systems in the range of 50,000–100,000 cfm. The method of use for these data in modifying operating cost estimates to alternative bases is presented in the Introduction to Chapter VII.

## TABLE VII-19

## COST DISTRIBUTION FACTORS FOR AIR POLLUTION CONTROL

**Systems**

1. **Settling Chambers**

| | |
|---|---|
| Capital Charges | 100% |
| Maintenance | 0 |
| Power | 0 |
| Water | 0 |
| Total | 100% |

2. **Centrifugal Collector** $\Delta P$ = 3.5 in. $H_2O$

| | Operating Schedule | | |
|---|---|---|---|
| | 2000 hr/yr (1 shift) | 4000 hr/yr (2 shifts) | 6000 hr/yr (3 shifts) |
| Capital Charges | 70% | 55% | 45% |
| Maintenance | 7 | 8 | 10 |
| Power | 23 | 37 | 45 |
| Water | 0 | 0 | 0 |
| Total | 100% | 100% | 100% |

3 **Centrifugal Collector** $\Delta P$ = 5 in. $H_2o$

| | Operating Schedule | | |
|---|---|---|---|
| | 2000 hr/yr (1 shift) | 4000 hr/yr (2 shifts) | 6000 hr/yr (3 shifts) |
| Capital Charges | 67% | 52% | 42% |
| Maintenance | 7 | 8 | 9 |
| Power | 26 | 40 | 49 |
| Water | 0 | 0 | 0 |
| Total | 100% | 100% | 100% |

4. **Wet Collector** $\Delta P$ = 5 in. $H_2O$

| | Operating Schedule | | |
|---|---|---|---|
| | 2000 hr/yr (1 shift) | 4000 hr/yr (2 shifts) | 6000 hr/yr (3 shifts) |
| Capital Charges | 51% | 36% | 28% |
| Maintenance | 11 | 11 | 12 |
| Power | 14 | 20 | 22 |
| Water | 24 | 33 | 38 |
| Total | 100% | 100% | 100% |

5. **Wet Collector** $\Delta P$ = 15 in. $H_2O$

| | Operating Schedule | | |
|---|---|---|---|
| | 2000 hr/yr (1 shift) | 4000 hr/yr (2 shifts) | 6000 hr/yr (3 shifts) |
| Capital Charges | 51% | 35% | 27% |
| Maintenance | 10 | 11 | 11 |
| Power | 24 | 33 | 38 |
| Water | 15 | 21 | 24 |
| Total | 100% | 100% | 100% |

6. **Fabric Filter**

| | Operating Schedule | | |
|---|---|---|---|
| | 2000 hr/yr (1 shift) | 4000 hr/yr (2 shifts) | 6000 hr/yr (3 shifts) |
| Capital Charges | 70% | 58% | 50% |
| Maintenance | 21 | 27 | 31 |
| Power | 9 | 15 | 19 |
| Water | 0 | 0 | 0 |
| Total | 100% | 100% | 100% |

7. **Electrostatic Precipitator - 95% efficiency**

| | Operating Schedule | | |
|---|---|---|---|
| | 2000 hr/yr (1 shift) | 4000 hr/yr (2 shifts) | 6000 hr/yr (3 shifts) |
| Capital Charges | 87% | 78% | 71% |
| Maintenance | 4 | 6 | 7 |
| Power | 9 | 16 | 22 |
| Water | 0 | 0 | 0 |
| Total | 100% | 100% | 100% |

8. **Electrostatic Precipitator - 99% efficiency**

| | Operating Schedule | | |
|---|---|---|---|
| | 2000 hr/yr (1 shift) | 4000 hr/yr (2 shifts) | 6000 hr/yr (3 shifts) |
| Capital Charges | 86% | 77% | 71% |
| Maintenance | 5 | 6 | 7 |
| Power | 9 | 17 | 22 |
| Water | 0 | 0 | 0 |
| Total | 100% | 100% | 100% |

### 7. Air Pollution Control System Selection

An acceptable incinerator air pollution control system serves the function of reducing the pollutant concentration in the flue gases from that prevailing at the inlet of the APC device, to a level which is equal to or lower than desired or prescribed by the local emission codes. The APC efficiency needed to meet this criterion is dependent upon the plant design, operating practices, and the refuse composition, as these factors are reflected in the inlet concentrations of pollutants. Since the desired effect for APC systems is usually the reduction of particulate matter, the subsequent discussions are oriented toward meeting particulate emission codes.

The APC equipment selected to meet a given efficiency will reflect the relative importance of investment versus operating cost trade-offs; and special local constraints, such as utilities cost and availability, operator qualifications, importance of steam plume formation to nearby residents, foundation requirements, and waste-water disposal problems. As a result, APC selection must be made on a case-by-case basis, taking into account the unique character of each plant location and the locally-established plant performance objectives.

The prime determinant in the selection of control equipment is the maximum amount of contaminant to be discharged to the atmosphere. With knowledge of this quantity, and knowledge of the amount of contaminant entering the collector, the required collection efficiency can be computed from the equation:

$$\text{Efficiency} = \frac{(\text{Entering Total Quantity} - \text{Leaving Total Quantity}) \times 100}{\text{Total Entering Quantity}}$$

It should be noted that "% Efficiency" as defined in this equation refers to *overall* particulate control efficiency. In reality, the efficiency should be developed as a sum of fractional efficiencies for different particle-size ranges as shown in Table VII-15. Table VII-5 shows the variability of inlet dust particle-size distribution incinerators. It would be expected that a given APC system would perform differently on each kind of dust. For the purposes of this evaluation, however, the anticipated overall particulate efficiency was based on the nominal particle-size distribution (see U.S.A. No. 2 -- pg. VII-14) and the associated APC efficiencies developed above.

The initial step in estimating the efficiency requirements for any pollution control system is the estimation of the entrance loadings. It is preferable, in the case of existing plants, to carry out a sampling program to determine the actual dust loading and particle-size distribution. Consideration should also be given to modifying the plant equipment or operating practices, as described in Chapter VII, Section C, to reduce the inlet loading, thereby reducing efficiency requirements (and cost) of the APC device. Alternatively, as an approximation, the emission factors presented in Table V-17 can be used to provide a preliminary estimate.

The second quantity needed for the efficiency calculation is the permissible dust loading of the gases leaving the plant. This can be established by review of local codes, taking into consideration the future changes in the code toward more stringent control, and allowing some conservatism to reflect future changes in refuse composition and some slow degradation in plant performance over the years. As an example of the approach using emission factors, Table VII-20 illustrates the development of an equipment efficiency requirement.

When the necessary particulate collection efficiency has been established, reference should be made to Figure VII-15 and/or Figure VII-16, both of which indicate the relationship between collection efficiency and total annual cost (including capital charges), as developed above. From these data, it can be seen that no devices offer superior control efficiency at low cost. Allowing for some variation of efficiency, both above and below the indicated data points, it can be seen that for any given efficiency range, several alternative air pollution control systems are available.

After candidate air pollution control systems and estimated operating costs have been identified, on the basis of efficiency requirements developed as in Table VII-20 and from the efficiency-cost curves on Figures VII-15 and VII-16; the reader is referred to Parts 4 and 5 of Section B, which discuss the anticipated abatement performance and operating characteristics of the candidate systems. Part 6 presents the investment and operating costs for various systems and the means to develop cost estimates specific to the plant location, using the techniques discussed in the Introduction to Chapter VII.

In addition to efficiency and cost considerations, a number of other system characteristics may be of importance, particularly that of space. Table VII-21 summarizes the relative in-plant space needs for the APC system (disregarding auxiliary facilities such as settling points, clarifiers, and the like). Other factors, such as waste water disposal and foundation requirements, must be evaluated on an individual basis.

## TABLE VII-20

## EXAMPLE OF ESTIMATION METHOD TO ESTABLISH PARTICULATE APC SYSTEM COLLECTION EFFICIENCY REQUIREMENTS FROM EMISSION FACTORS AND REFUSE COMPOSITION

Assume that the incinerator is of the refractory wall, traveling grate type, built in 1963 (22 years of remaining useful life - until 1985), and assume each of the following refuse ash examples:

1. From Table V-17, the 1968 nominal emission factor is 12.8 lb of mineral particulate and 3.9 lb of combustible particulate (total of 16.7 lb) per ton of refuse.

2. Based on an assumed local refuse analysis, present (1968) average refuse ash content (excluding metal and glass) is 6.2%; therefore, from Table V-17, mineral particulate emissions in this plant could approximate (0.062) (236) = 14.6 lb/ton of refuse (18.5 lb/ton total particulate).

3. It is expected that the average ash content of refuse in the general plant area (assumed in this example to be a seasonal state) will change according to the following:

   (a) From Table IV-15, the average refuse ash content in 1968 (excluding metal and glass) in a seasonal state is 5.53%.

   (b) From the same table, the average refuse ash content in 1980 (excluding metal and glass) in a seasonal state is 5.22%.

   Therefore, it appears that in this case, *average* refuse ash composition will not change appreciably. (This is not always true; one should carefully consider anticipated *local* refuse composition changes).

4. Some present codes still limit maximum particulate emission to 0.85 lb of particulate per 1000 lb of flue gas corrected to 50% excess air (lb/Mlb @ 50%) but anticipated codes, in this example, will be assumed to require control to 0.3 lb/Mlb @ 50%.

5. The conversion factor of 11.27 lb/Mlb @ 50% per 1.0 lb/ton of refuse is then obtained from Table VI-1.

6. It can, therefore, be seen that:

| | | **Emissions** | | **Code (lb/Mlb@50%)** | | **Minimum** |
|---|---|---|---|---|---|---|
| | **Emission Estimate Source** | **lb/ton of Refuse** | **lb/Mlb @ 50%** | **Present** | **Forecast** | **Required Efficiency** |
| a. | Nominal Emission | 16.7 | 1.48 | 0.85 | | 43% |
| | (1 above) | | 1.48 | | 0.30 | 80% |
| b. | Maximum Emissions | 18.5 | 1.64 | 0.85 | | 48% |
| | (2 above) | | 1.64 | | 0.30 | 82% |
| c. | Maximum Emissions (2 above) plus 20% safety factor | 22.2 | 1.96 | 0.85 | | 57% |
| | | | 1.96 | | 0.30 | 85% |

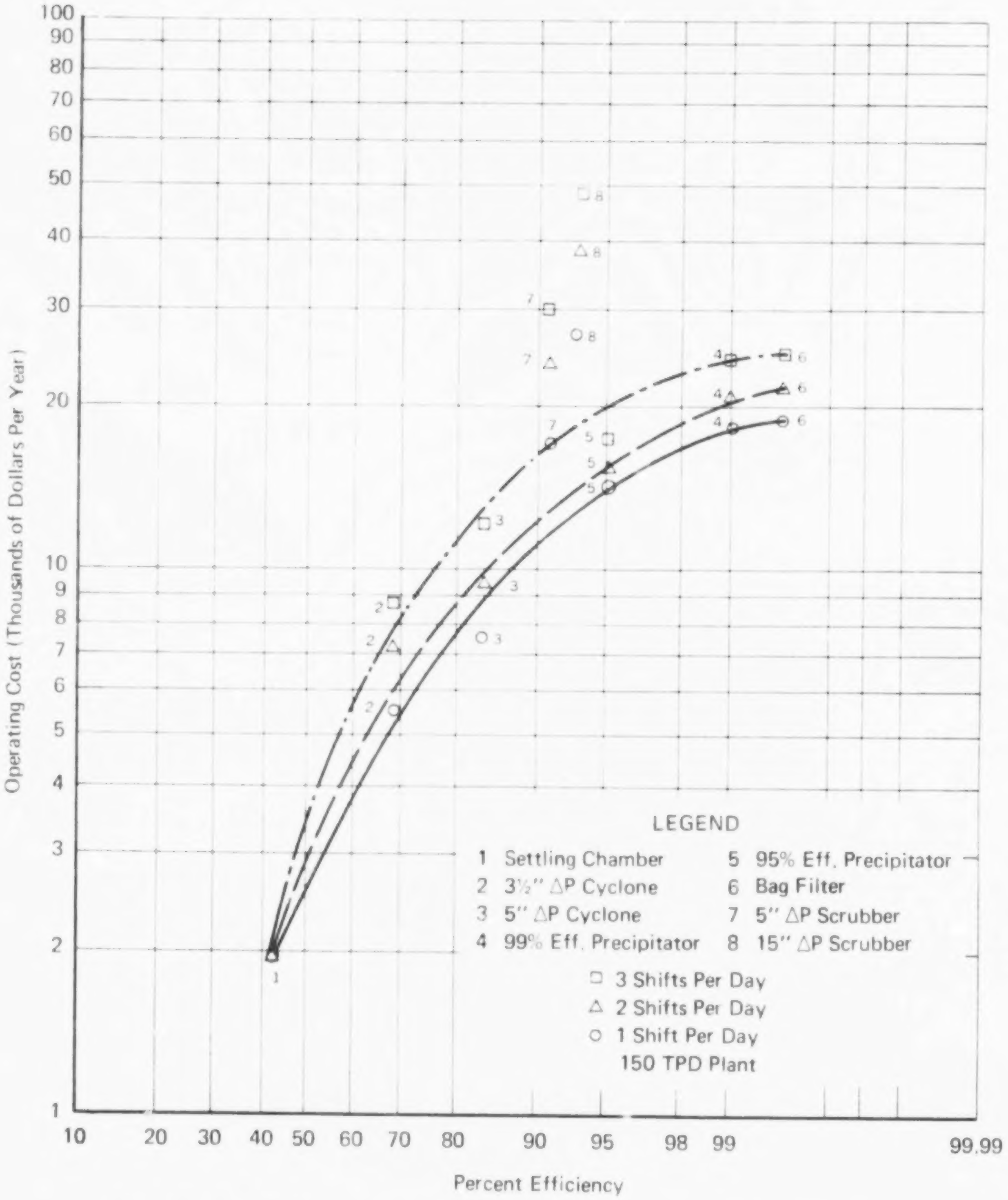


FIGURE VII–15 TOTAL ANNUAL OPERATING COST VERSUS PARTICULATE REMOVAL EFFICIENCY 150 TPD PLANT; 1, 2, & 3 SHIFT OPERATION

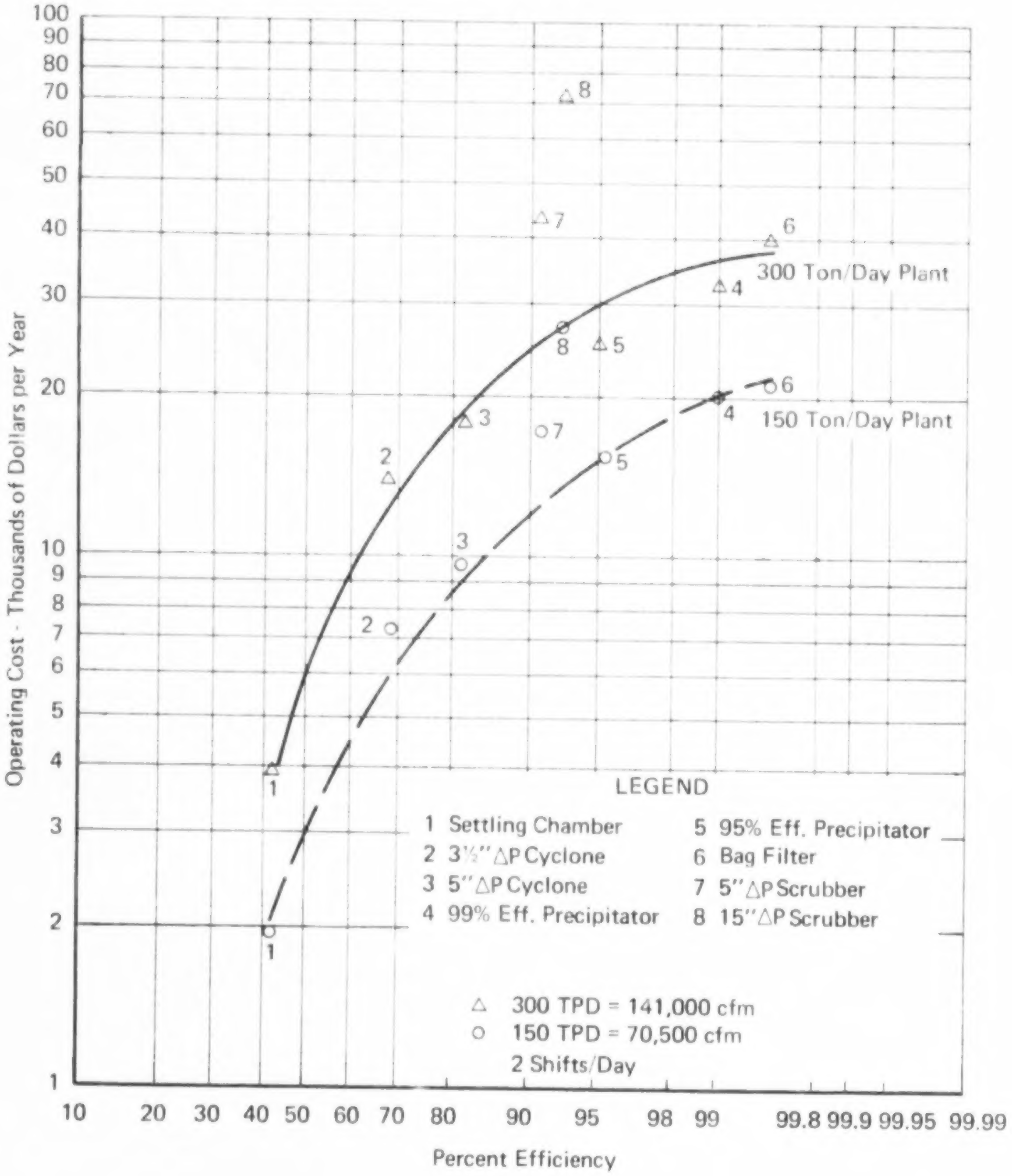


**FIGURE VII–16** TOTAL ANNUAL OPERATING COST VS. PARTICULATE REMOVAL EFFICIENCY–150 AND 300 TPD PLANT; 2-SHIFT OPERATION

## TABLE VII-21

## RELATIVE IN-PLANT SPACE REQUIREMENTS FOR AVERAGE AIR POLLUTION CONTROL SYSTEMS[39]

| Equipment Type | Relative Space Requirement |
|---|---|
| Electrostatic Precipitator | 90% |
| Scrubber – Spray type | 50% |
| Flooded Plate | 30% |
| Venturi | 25% |
| Mechanical Cyclone – Multiclone | 25% |
| 60″ dia. tangential inlet | 30% |
| wetted wall | 25% |
| Baghouse filter | 100% |
| Settling chamber with sprays | 60% |

## C. TECHNICAL-ECONOMIC ANALYSIS–MODIFICATIONS TO EXISTING PLANT

The municipal incinerator plants which are presently operating will be the dominant source of incineration air pollution until the mid 1970's. Although a large portion of this report and many current and anticipated research efforts support the development of systems producing little air pollution, modification of existing plants offers the greatest potential for near-term reduction of incinerator emissions. The working life of an incinerator plant is about 25 years. The replacement value of existing equipment approximates $500 million. Clearly, this initial investment cannot be discarded. However, the air pollution problems associated with many of these plants cannot be allowed to continue.

The imperfect performance of existing incinerators can be corrected. The cost of correction varies widely. In some cases, substantial improvements can be effected at essentially no cost by changes in operating practices. In other cases, major revisions to the incineration facility must be made. Such modifications must be carefully evaluated as the solution for one problem should not be the cause of another. Any solution must be consistent with meeting the overall goals of solid waste disposal: a minimum of cost and environmental pollution, and a maximum of safety, reliability, and residue quality.

### 1. Purposes

The purposes of this portion of the report (which is supported by Appendix K) include:

- Indicating the symptoms of poor incinerator performance as an aid in air pollution problem evaluation;
- Describing the causes for each symptom of poor incinerator performance as an aid in suggesting aspects of the plant design or operating practices which could underlie the symptom;
- Suggesting modifications of the plant or alternate operating procedures to correct such deficiencies, and evaluating the potential cost and effectiveness of the corrective action; and
- Alerting the problem-solver to the implications of a given corrective action as regards other aspects of overall performance.

To serve broad needs, the analysis is general in nature, but comprehensive in scope. A problem-solving methodology is suggested which hopefully will increase the usefulness of the analysis in evaluating problems. Mechanisms are provided for adjustments and updating of the cost data to improve estimating accuracy for specific geographical areas and chronology.

### 2. Limitations of the Analysis

This analysis has limitations. No problem solver could ever write a document which would provide definitive, final answers applicable across the wide range of incinerator types and ages characterizing the U.S. incinerator industry. Thus, the subsequent paragraphs are necessarily general. The suggestions cannot replace the contributions of competent engineers experienced with any particular plant. Cost estimates, for example, require adjustments to reflect local labor costs and productivity; special equipment and freight costs; and unusual site preparation, foundation, architectural and off-site costs. Even after such adjustment, the resulting costs should not be considered a basis for financing or budgeting. They are useful, however, for estimating the relative cost of alternatives and in suggesting "order-of-magnitude" costs as preliminary estimates.

A second limitation of this analysis is that it is necessarily dependent upon the user's honest, thoughtful, and comprehensive appraisal of the problem. Denying past errors in judgment or the inadequacy of long-standing operating practices, or subjective distortion of the current state-of-affairs rapidly degrades the utility of the analysis and the applicability of its suggestions.

Perhaps the most important deficiency of this analysis is the industry's limited knowledge of the quantitative relationships between operating and design variables and performance. Although incinerators have been built and operated in this country for most of this century, little basic data which one can use to analyze the incineration process actually exist. This deficiency reflects the lack of incentives, the cost, and the difficulty of conducting such experiments. The net result is, however, that practical experience and engineering judgment are often the only resources available to evaluate the impact of parameter variations on performance.

In addition to the lack of quantitative knowledge about incinerator operation, a secondary problem arises because of the intangible, poorly defined, geographically variable, or hard-to-measure criteria for "good versus bad" performance of an incinerator.

### 3. Approach

Selecting different courses of action requires consideration of the ultimate criteria for successful incinerator performance: viz., reliability, low environmental pollution, safety, good residue quality and low cost per ton processed. To meet overall solid waste disposal objectives fully, attention must be paid to achieving quality performance in each of these five areas. These subjects have been discussed in detail in Appendix H to suggest benchmarks against which to judge the quality of present or future plant performance goals.

In carrying out this analysis, many aspects of equipment and operating practices were considered in order to develop a comprehensive list of problems. Consistent with the general approach necessary for this presentation, specific items of equipment are not discussed. We did not, for example, examine the problem of corrosion failure of scrubber water pump seals, but rather the general maintenance or design weaknesses (including the absence of spares) which contribute to equipment failure.

We decided that the most useful way of organizing the suggested plant modifications was in relation to the various criteria of performance rather than to specific operations within the incineration plant, or according to the specific items of equipment throughout the plant. By this means the visible problems in plant performance were emphasized rather than the details of which piece of equipment failed to perform and in what way.

Subsequent analysis of the problems suggested probable causes. Once causes were defined, solutions could be proposed and evaluated. In more cases than not, the quantitative effect of a change in design or operation could not be determined. Conclusions such as "a 5% change in this parameter causes a 20% change in another" are not supported by the meager engineering data base. Many depend on operator cooperation; all demand a measure of commitment by the municipality.

After a solution had been found for a given reason for unsuccessful incinerator performance, it was necessary to consider the interrelationship between the action taken to solve the problem and other incinerator performance criteria. As an incinerator is a complex system, modification of one part can have serious implications on the design requirements or operating characteristics of other parts of the system. One should not, for example, increase the underfire air rate to increase the burning rate without considering the resulting effect on particulate carry-over. For this reason, a simple key was developed to alert the reader to the interaction of proposed solutions with other aspects of the incinerator design or operating characteristics.

The plant problems of particular interest in this report concern the reduction of air pollution from incineration. The solutions to air pollution problems fall into two categories; viz., installation of control equipment or the modification of operating practices. To reduce particulate emissions, installation of APC equipment (discussed in Section VII-B) usually represents the best solution. Changes in operating practices are useful as interim methods to reduce emission until proper APC equipment can be installed, or to reduce the necessary control efficiency (cost) by minimizing the inlet loading. Control of combustible pollutants, however, is best accomplished by changes in operating practices, APC equipment being marginally effective or noneffective for these pollutants.

An important alternate use of this portion of the report (and Appendix K which presents the detailed problem-solving discussions) is in identifying the interactions between *current* operating practices and air pollution emissions. It may be, for example, that present plant practices, some of which may have developed arbitrarily, contributed indirectly to increased emissions. A review of Appendix K may identify such practices and suggest alternates.

### 4. Problem-Solving Method

Improving existing solid-waste incineration facilities is the goal of almost every plant superintendent, city engineer, and municipal official. Often, however, the plant superintendent's time is spent in day-to-day problem-solving to maintain the plant in operating condition. His intense involvement in plant operation and an insufficient capital expenditures budget tend to give him a nearsighted view of plant problems and requirements. The city engineer is often aware of the need to improve plant performance, but he is unsure of the best means to accomplish this objective. The municipal official is involved in trying to meet a wide spectrum of community demands, only one of which is solid waste disposal.

These key men have a common need for a structured evaluation and decision-making tool; one building logically from plant performance objectives which are visible and understandable to municipal officials, to a level of detail where specific actions are identified.

Figure VII-17 presents a decision diagram for performance improvement. The following paragraphs discuss each of the steps shown in this figure.

- Review of Plant Performance Objectives

  The initial step is a review of the plant performance objectives. These objectives are discussed in Appendix H. Such a review should consider all performance criteria applicable to the incineration system in the context of local economics, community needs, and aspirations.

- Review of Performance and Comparison of Performance with Objectives

  In comparing these objectives with the plant performance record, performance deficiencies will undoubtedly be identified. These deficiencies can be grouped in terms of the five overall solid-waste disposal objectives.

- Identification of Problem Type (Symptoms)

  Pursuing these deficiencies in greater depth will result in the identification of general problems or "symptoms." In the context of this report, a symptom is a highly visible or measurable problem impinging directly upon one of the performance criteria. For this use, a list of such symptoms is presented in Table VII-22.

- Detailed Analysis of Problem to Identify Specific Problems (Causes)

  At this point, the analysis becomes more detailed and requires contributions from both engineering and plant personnel to identify specific problems or "causes" for the symptoms. Typically, a symptom may have a number of different causes; reflecting deficiencies in design, maintenance, or operating practices.

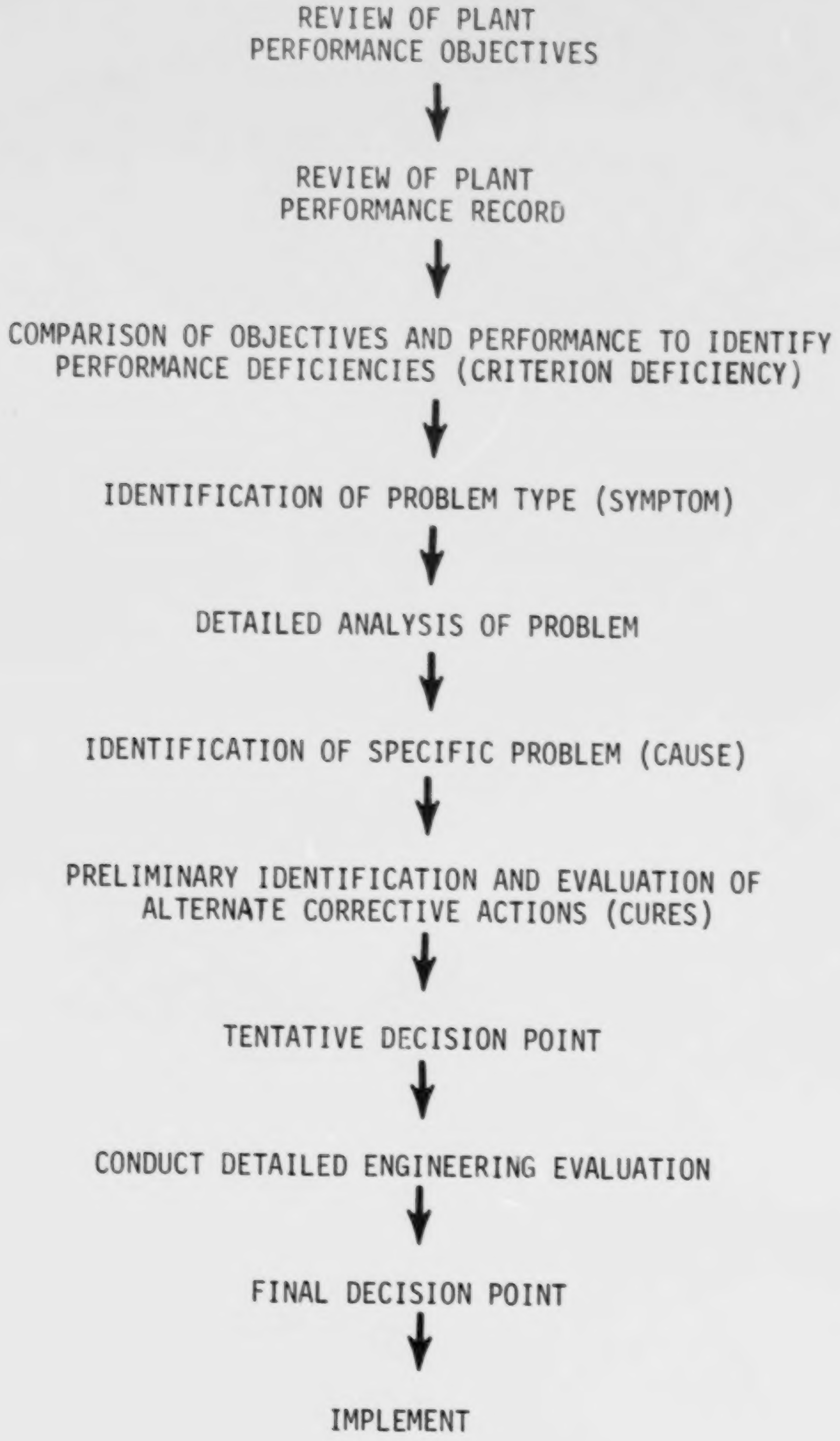

REVIEW OF PLANT PERFORMANCE OBJECTIVES
REVIEW OF PLANT PERFORMANCE RECORD
COMPARISON OF OBJECTIVES AND PERFORMANCE TO IDENTIFY PERFORMANCE DEFICIENCIES (CRITERION DEFICIENCY)
IDENTIFICATION OF PROBLEM TYPE (SYMPTOM)
DETAILED ANALYSIS OF PROBLEM
IDENTIFICATION OF SPECIFIC PROBLEM (CAUSE)
PRELIMINARY IDENTIFICATION AND EVALUATION OF ALTERNATE CORRECTIVE ACTIONS (CURES)
TENTATIVE DECISION POINT
CONDUCT DETAILED ENGINEERING EVALUATION
FINAL DECISION POINT
IMPLEMENT

FIGURE VII-17

DECISION DIAGRAM FOR PERFORMANCE IMPROVEMENT

## TABLE VII-22

## GENERAL SYMPTOMS OF INCINERATOR DEFICIENCIES AFFECTING CRITERIA OF PERFORMANCE

### CRITERION I: ENVIRONMENTAL POLLUTION

**A. Air Pollution**

| | | Appendix K Page No. |
|---|---|---|
| 1. | Excessive Non-combustible Particulate Emission | K- 3 |
| 2. | Excessive Emissions of Non-combustible Gaseous Pollutants ($SO_2$, $NO_x$, HCl) | K-10 |
| 3. | Excessive Emissions of Combustible Pollutants (Smoke, CO, Hydrocarbons, Carbon) | K-12 |
| 4. | Inadequate Dispersal of Stack Gases | K-19 |
| 5. | Dusting of Refuse in Pit | K-20 |
| 6. | Dusting of Residue at Disposal Site | K-20 |
| 7. | Odors Emanating from Pit | K-20 |
| 8. | Odors Emanating from Stack | K-20 |
| 9. | Odors Emanating from Settling Pond | K-21 |
| 10. | Odors Emanating from Residue Disposal Site | K-21 |
| 11. | Odors Emanating from Residue Trucks | K-21 |
| 12. | Exhaust Emission of Delivery and Residue Trucks | K-21 |

**B. Water Pollution** (resulting from seepage or discharge of inadequately treated liquids) **From -**

| | | Appendix K Page No. |
|---|---|---|
| 1. | Refuse Pit | K-22 |
| 2. | Residue Quench Water | K-22 |
| 3. | Flue Gas Conditioning System or APC Device | K-22 |
| 4. | Settling Ponds | K-22 |
| 5. | Residue Disposal Site | K-23 |
| 6. | Wash-down Waters | K-23 |

**C. Aesthetics**

| | | Appendix K Page No. |
|---|---|---|
| 1. | Shoddy Appearance of Site and Mobile Equipment | K-23 |
| 2. | Refuse Blowing Away from Pit during Dumping | K-24 |
| 3. | Refuse Accumulating in Excess of Pit Storage Capacity | K-24 |
| 4. | Spillage of Refuse During Handling and Feeding | K-25 |
| 5. | Noise | K-25 |
| 6. | Odor | K-26 |
| 7. | Heavy Traffic | K-26 |
| 8. | Vermin | K-26 |
| 9. | Plume Visibility | K-26 |

**D. Health Hazards** (due to breeding of disease vectors) **at -**

| | | Appendix K Page No. |
|---|---|---|
| 1. | Refuse Pit | K-27 |
| 2. | Residue Disposal Site | K-28 |
| 3. | Settling Pond | K-28 |

Appendix K
Page No.

## CRITERION II: POOR RESIDUE QUALITY

1. Physical Appearance K-29
    Readable Printed Matter
    Identifiable Food Materials
    Unoxidized Cans
2. Residue Burning or Smoking K-29
3. Presence of Vermin and/or Birds at Dump Site K-29
4. Inadequate Volume and Weight Reduction K-29
5. Residue Odor K-29
6. Analysis of Residue K-29

## CRITERION III: POOR RELIABILITY
### (Excessive Unscheduled Down-Time)

1. Equipment Failure K-32
2. Congestion or Plugging of Gas Passages K-34
3. Slag Build-up Interfering with Grate Operation K-38
4. Failure of Utilities K-38
5. Hazardous Occurrences K-39
    Burning Under Grates
    Refuse Pit Fires
    Smoking From Primary Chamber
    Feed Chute Fires
6. Inadequate Spare Parts Inventory K-42
7. Labor Problems K-42
8. Governmental or Judicial Actions (Injunctions) K-42

## CRITERION IV: PERSONNEL SAFETY CONSIDERATIONS

**Employee Injuries From –**

1. Unsafe Practices K-43
2. Objects Expelled from Primary Combustion Chamber K-43
3. Burns K-44
4. Falls K-44
5. Equipment K-45
6. Fires K-45
7. Dust Inhalation K-45
8. Accidents to Employees and Trespassers at the Residue Disposal Site K-46

## CRITERION V: EXCESSIVE COST PER TON FOR INCINERATION AND RESIDUE DISPOSAL

1. Burning Less Than Planned Annual Capacity K-47
2. High Maintenance Cost Per Ton of Refuse Processed K-47
3. Excessive Utilities Consumption Per Ton of Processed Refuse K-48
4. High Labor Costs Per Ton of Refuse Processed K-49
5. High Residue Disposal Costs K-50

- Preliminary Identification and Evaluation of Alternate Corrective Actions (Cures)

  The next level of analysis is the preliminary evaluation of alternate corrective actions or "cures" for the causes. Such an evaluation explores alternate cures for a given problem relative to technical suitability, economic acceptability, freedom from disadvantageous interactions with other desirable performance characteristics, and risk. The latter consideration reflects the uncertain effectiveness of a given cure due to gaps in technical understanding, labor realities, etc. Causes and associated cures for the symptoms of poor incinerator performance are presented in semi-outline form in Appendix K. Discussion of the technical suitability and economic acceptability of some of the alternate cures is incorporated in the outlines. The predominant weight of detail is in the area of cures directly affecting the air pollution problems of the incinerator.

  An important aspect of problem-solving is assuring that the solutions chosen to solve one problem do not inadvertently create another. To assist in determining the interaction between the cures suggested and other aspects of incinerator performance, each cure which has a significant interaction with other aspects of incinerator performance is keyed by a number. Other pages in the outline which indicate problems having the same interactive characteristic are designated by a similar key number at the right margin. If, for example, to reduce unit costs, it is suggested that the underfire air rate should be increased (to increase burning rate and throughput), this cure is keyed to a suggestion to reduce underfire air level to minimize particulate carry-over and consequent high air pollution emission problems. Thus, to the extent possible, the reader is alerted to a possible problem in implementation of the cure.

- Tentative Decision Point Followed by a Detailed Engineering Evaluation

  Following such a preliminary review of alternatives, a tentative decision can be reached as to which of the cures should be evaluated in greater depth. At this point, a detailed engineering evaluation should be conducted to provide the detailed budgeting estimates and to assess the risks associated with the proposed modifications.

  Figure VII-18 suggests the general types of cures arising from such an analysis classified as they reflect design, maintenance, and operating deficiencies. It is noteworthy that revising performance objectives

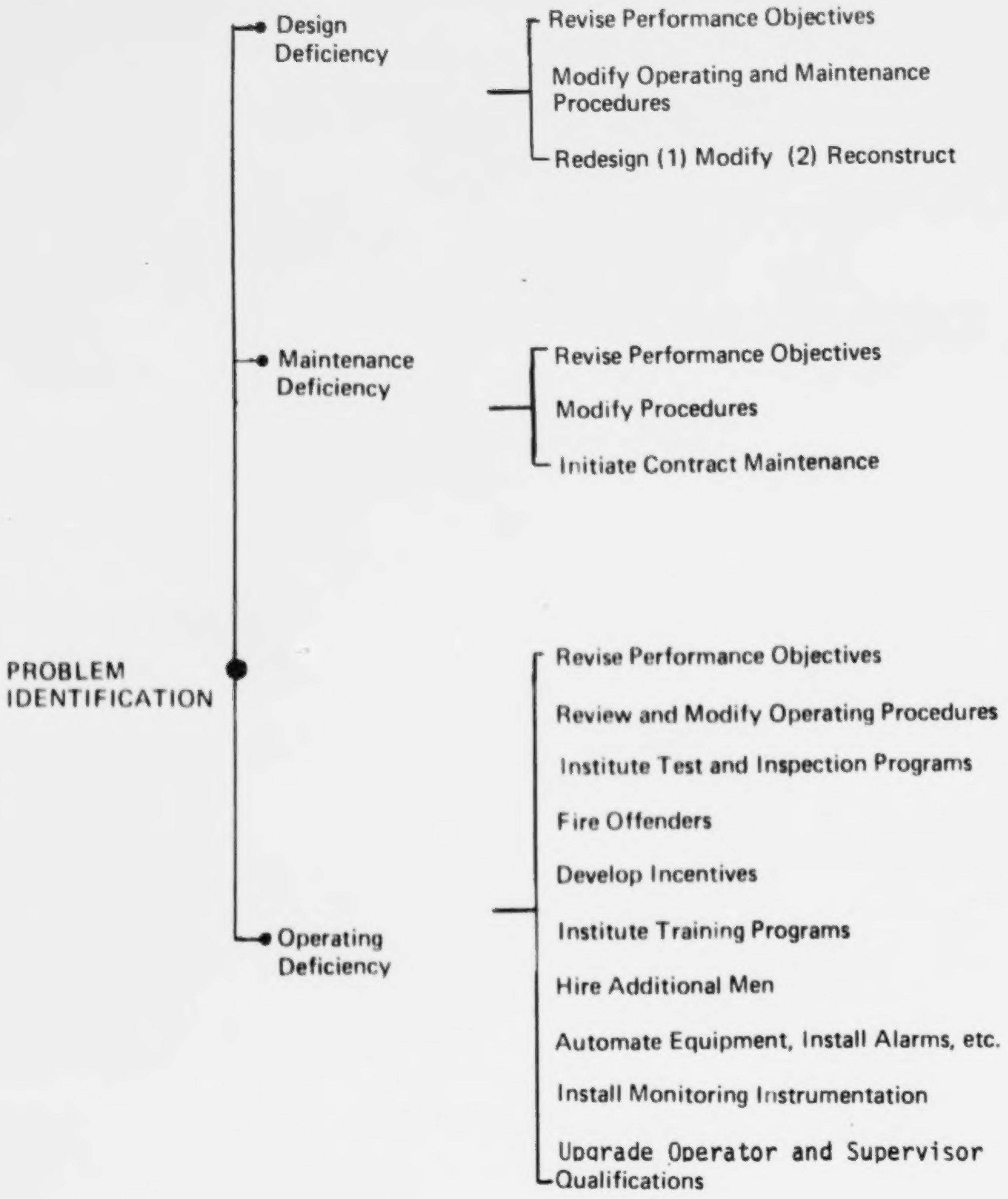

Design Deficiency
Revise Performance Objectives
Modify Operating and Maintenance Procedures
Redesign (1) Modify (2) Reconstruct
Maintenance Deficiency
Revise Performance Objectives
Modify Procedures
Initiate Contract Maintenance
PROBLEM IDENTIFICATION
Operating Deficiency
Revise Performance Objectives
Review and Modify Operating Procedures
Institute Test and Inspection Programs
Fire Offenders
Develop Incentives
Institute Training Programs
Hire Additional Men
Automate Equipment, Install Alarms, etc.
Install Monitoring Instrumentation
Upgrade Operator and Supervisor Qualifications

**FIGURE VII–18**

**ALTERNATIVES FOR PERFORMANCE IMPROVEMENT**

downward may be an allowable answer; it may be that in the context of local priorities, no action can be taken. It is of value, however, to recognize the compromises which have been made and, perhaps, to seek performance objectives, while still effecting an improvement over the existing situation. It should also be noted that substantial improvements can often be made without large capital investments, by modifying existing operating and maintenance practices.

- Final Decision Point and Implementation

  Following the detailed engineering evaluation of the proposed modifications, a final decision can be made as to which modifications are most consistent with the objectives of the plant. These modifications should then be implemented by competent engineering and construction firms.

### 5. Identification of System Interactions

Following the evaluation methods described above, the reader will be able to identify one or more "cures" which seem appropriate to solve his current plant problems. There is, however, a possibility that implementation of a given cure will create new problems affecting other aspects of plant performance. To show such interactions, the "cures" have been reviewed and their effect on various plant parameters evaluated. These parameters are:

| **Parameter Number** | **Parameter** |
|---|---|
| 1 | Waste-water generation |
| 2 | Plant operating costs (excluding debt cost) |
| 3 | Underfire air |
| 4 | Overfire air |
| 5 | Flue gas volume flow rate |
| 6 | Flue gas mixing |
| 7 | Plant safety |
| 8 | Grate damage |
| 9 | Refuse composition and properties |
| 10 | Pit holding time |
| 11 | Refuse firing rate |
| 12 | Stoking characteristics |
| 13 | Moisture content of flue gases |
| 14 | Combustion control |
| 15 | Fan capacity |
| 16 | Siftings problems |

In Appendix K (Causes and Cures for Incinerator Deficiencies Affecting Criteria of Performance), where causes and cures are discussed in detail, each cure which was felt to have a significant effect on one or more of these parameters was marked with circled numbers, designating the parameter number. The following example shows the appearance of the text ①

Cure 1. – Reduce overfire air velocity ④ ⑥ ⑭

Cure 2. – Moisten refuse ① ⑬ ⑭ ④

For cure 1, as an example, the Parameter Numbers 4, 6, and 14, suggest that prior to implementing cure 1, the reader should consider other incinerator problems which are also influenced strongly by overfire air, flue gas mixing, and combustion control. These other problems (also marked with the number or numbers 4, 6, or 14), are those which could be significantly improved or worsened by carrying out cure 1. This process will usually identify considerations which both support and detract from the decision to carry out a given cure. The judgment as to which of the effects is most important must be determined by the reader in the context of his unique needs and plant situation. ⑥

To facilitate the process of finding these related problems as they appear throughout the text, the parameter numbers associated with each cure are also typed in the margin of the page on which the cure discussion first appears. Continuing with the example for cure 1, the reader who has tentatively decided to implement cure 1 should page through the *entire* Causes and Cures section of the report to identify and read of other plant problems which have been similarly marked with parameters 4, 6, or 14. To assist the reader in the mechanics of this process, the final page of the causes and cures text is a fold-out which lists the parameters and parameter numbers; indicates where along the margin the parameter numbers will appear; and provides spaces for notes and references (page K- 57 ).

There is no question that this is a laborious process. If it is done carefully, however, the reader will hopefully have before him a comprehensive picture of the impact of a proposed solution to a given problem on the total incineration system. If this appears difficult or complicated, it is, at least partly, a reflection of the complexity of an incinerator. "Cookbook" answers to plant problems seldom exist. ⑬ ⑭

The problem solving methodology described above and the detailed evaluation outline in Appendix K suggest definite actions to reduce incinerator air pollution and to improve overall incinerator performance. Implementation of many of these actions by municipal incinerator owners/operators could make a substantial improvement in the near-term incinerator air pollution levels forecast in Chapter VI. In general, the annual costs to the communities involved would be low. Realization of this fact by the people and by the local governments and commitment to improved air quality is needed.

## D. TECHNICAL-ECONOMIC ANALYSIS—INCINERATION CONCEPTS BASED ON EXISTING TECHNOLOGY

The growing demand for new solid waste disposal facilities in municipalities throughout the country stresses the need for a greater understanding of available techniques for refuse incineration. An appreciation of the technical and economic merits of the various concepts will allow the municipality to make more comprehensive decisions in selecting the type of incineration facility best suited for its needs. However, the need for consultation between municipalities and competent engineering firms is still very important.

When evaluating an incineration concept, there are different, and often competitive, criteria by which performance is judged. The principal criteria applicable to incineration – reliability, residue quality, environmental pollution, safety and cost (Appendix H, Section D) – should be carefully considered in determining the performance levels which a municipality desires from its incineration facility. For example, if the air pollution control regulations are stringent and plans have been formulated to utilize the incinerator residue for road bed applications, the municipality should strongly consider a highly efficient combustion system and air pollution control device. These environmental control and residue quality requirements, as well as the ever-present criteria of cost, will, therefore, determine the type of system best suited for this municipality.

### 1. Purpose

In this section we provide technical and economic information to help in the selection of an incineration concept once the level of performance desired for each of the five performance criteria has been established. For each incineration concept, a description of the distinguishing technical features of the process is presented, together with the advantages and disadvantages inherent in the system concept. Also discussed are weaknesses or potential problems not inherent in the concept, but which could be averted with experience or research. In addition, an economic analysis of each concept is developed. This analysis covers both the capital investment costs, the total operating costs for these concepts, and the influence of such variables as economics of scale and labor requirements on the magnitude of costs.

The air pollution potential of each process concept is discussed on the basis of measured or estimated furnace emission factors. (See Chapter V, Section VII-C, and Appendix K for suggestions as to the importance of the various design and operating characteristics as they affect air pollutant emissions and other aspects of overall plant performance. In a sense, the reader seeking guidance in incinerator selection is in the position of a plant operator reviewing what he wishes he had done correctly in the beginning.)

All plants have been evaluated for the same APC system (99% efficient electrostatic precipitator). This is not an evaluation at the same level of emission because of differences in the anticipated emissions between different incinerator types. By this means, however, the costs associated with the APC system (section VII B-7) may be readily subtracted from the cost for any of the systems discussed using a single value (for similar capacities and operating schedules). Alternatives can then be readily substituted.

For most of the incineration concepts discussed, the portion of the total capital cost for the electrostatic precipitator is shown explicitly. In general, the cost of this high-performance control system is still only 10% of the total investment. Too often the APC device, an increasingly important contributor to acceptable incinerator performance, is the first to be cut back if the construction costs exceed the appropriation. Since APC systems comprise such a small part of the total construction budget, however, the ultimate level of control obtained for the plant is highly vulnerable to such budget reductions. Clearly, more realistic budgeting and some realignment of priorities is necessary.

### 2. Limitations

The primary limitation of this portion of this report lies in the direct applicability of the economic data. Although many of these data can be modified to align investment and operating costs with local cost factors, there are a number of other important considerations. Cost information, for example, assumes average foundation costs. If the load-bearing capability of the local soil is unusually low, pilings or other extensive foundation work will add significantly to the cost. Similarly, if the plant is to be built on bedrock, the blasting which may be required for the refuse storage pit will also add significantly to the cost. The primary utility of these estimates, therefore, lies in the comparison between concepts and in the visualization of the relative importance of various cost centers in the total operating cost evaluations.

To develop generalized investment costs, data from a number of sources were collected and analyzed. The principal data sources were the consulting engineers and equipment vendors. Also, data collected by the Bureau of Solid Waste Management and the limited published information was used. From this data bank, broad ranges of costs were outlined, reflecting in part the diversity of equipment options and also differences in local unit construction costs. The capital investment presentations for batch feed and continuous feed rectangular construction systems show the range of costs which were identified. These ranges are somewhat smaller than the raw data indicated as the effects of year and location of construction have been partially removed by use of Engineering News Record indices to bring all costs to the reference point of Boston, Massachusetts, in 1969. The residual variability in capital investment estimates, however, is ± 15-20%.

Operating cost estimates, including fixed charges, were based on reasonable assumptions regarding labor force, utilities costs, etc. Since the unit costs for the various components of operating cost vary widely, a mechanism was developed for simple conversion of our results to alternative bases.

### 3. Scope and Approach

Incineration concepts based on existing technology (Table VII-23), include a wide variety of systems, some of which are presently utilized and others which have not as yet been demonstrated in a full-scale incineration facility. In all cases, however, the basic technology exists, well-demonstrated, in the pyroprocessing, metallurgical, or other industries.

TABLE VII-23

INCINERATION CONCEPTS BASED ON EXISTING TECHNOLOGY

| | Page No. |
|---|---|
| – Batch Feed | |
| • Rectangular and Cylindrical | VII-94 |
| – Continuous Feed | |
| • Rectangular Construction | VII-103 |
| • Horizontal-Cylindrical Construction | VII-112 |
| • Ignition Grate Plus Burnout Kiln | VII-118 |
| • Volatilizing Kiln and Burnout Grate Construction | VII-127 |
| • 3-Stage Rotary Kiln Construction | VII-132 |
| • Waterwall Construction (Grate Burning) | VII-139 |
| • Waterwall Construction (Suspension Burning) | VII-147 |
| – Semi-Continuous Feed | |
| • Package System | VII-153 |
| • Rotary Grate | VII-159 |
| – Continuous Feed with Residue Fusion | VII-163 |

Associated with these incineration concepts are a variety of subsystems, each of which may significantly affect plant performance and economics. Feeding systems, for example, may involve a conventional refuse storage pit and crane or, alternatively, plants may be found with a refuse dumping and storage floor serviced with a front-end loader and slat conveyor system. Both dry and wet residue and siftings handling systems are utilized. Air pollution control systems may vary from simple spray and water impingement baffle systems to high-energy scrubbers, or electrostatic precipitators. Waste heat from the incinerator flue gases is recovered in some plants by the use of one of several available convective waste heat boiler designs. Metal recovery systems are also used to segregate and collect metals from the refuse or residue to yield operating revenues.

The type of building enclosing the incinerator also contributes to the wide variation in the cost of incineration facilities. Buildings vary from those using inexpensive sheet metal siding which encloses only portions of the furnaces to attractive, landscaped brick buildings costing as much as 50-60% of the total incinerator facility. In addition, variations in the topography of the land, the degree of sophistication of instrumentation and controls, the cost of local labor, and materials cost throughout the country compound the difficulty of comparing the design and costs of incineration facilities.

In order, then, to compare the technical and economic aspects of the various incineration concepts and their related subsystems, a common basis was selected. We assumed that no waste heat or metal recovery credits were taken, that refuse is fed from the pit directly to the furnace by means of a bridge crane and bucket, and that the incineration facility is on land which is suitable for construction without excessive site preparation. The instrumentation and controls utilized were those of typical modern existing incineration facilities.

The types of residue handling systems were not specified for each of these concepts. The differences in costs for alternative residue handling systems, when compared to the total furnace costs, are small and should not significantly influence the economic comparisons of alternative furnace concepts.

These assumptions were made only to retain some degree of uniformity in comparing the investment costs for the various incineration concepts being considered and are not an endorsement or condemnation of alternative subsystems (Appendix H, Section B). The economics for by-product recovery and for a variety of air pollution control systems were developed as modular costs (Appendix F and Section VII-B, respectively), so that investment costs of incineration facilities employing these subsystems can be readily estimated.

## 4. Batch Feed Incineration Systems

### a. Process Description (Appendix H)

Batch feed incineration, the oldest type of incineration system utilized by municipalities, is still in wide use. Most contemporary municipal batch feed incinerator systems consist of vertical cylindrical chambers or rectangular cell units, with capacities as low as a few tons a day and as high as 200-300 tons per day.

Most municipal batch feed incineration systems have a refuse pit for receiving and storing refuse and an overhead monorail or, preferably, traveling bridge crane to transfer the refuse to the feed hoppers. These incineration facilities generally use one crane to supply the refuse to one or two incinerator furnaces. There are, however, large multiple-furnace municipal facilities which consist of up to six, 200 TPD units; such large plants would use more than one crane.

Refuse accumulated in a feed hopper over the furnace is periodically charged by opening a sliding gate separating the hopper and the inside of the primary chamber. When the charging gate is opened furnace draft draws large quantities of air into the furnace, which is disadvantageous to the combustion process (Sections V and VII-B). Alternative batch feed techniques, however, such as a double-gate air-lock system or a ram feeder could alleviate this problem. The frequency of charging is determined by the rate of burning in the primary chamber, as indicated by the decrease in refuse bed height and drop in chamber temperature as the refuse is consumed.

The charging doors on vertical-cylindrical batch feed incinerators are directly above the grates. The refuse on the grates is stoked manually and/or mechanically by a rotating "cone" with extended air-cooled rabble arms. As the refuse is consumed, the ash is moved away from the center of the furnace by the rabble arms. Dumping grates (hand-cranked or hydraulically operated), located at the chamber periphery, are periodically lowered to discharge the accumulated ash. Water sprays are used to quench any glowing char in the ash hopper.

The charging doors of rectangular batch feed furnaces (cells) are in the middle or near the rear of the roof of each unit. The units with charging doors near the rear have inclined grates which are either fixed or mechanically movable. The refuse travels from the rear to the front of the furnace, with the resulting ash falling from the front of the grates to the residue handling and quenching system below. In some furnaces, a dump grate at the front of the furnace holds back the residue to improve burnout. A few plants discharge still-burning refuse to the ash pits and partially burn below the grates.

Batch-type incinerator systems are operated to maintain primary combustion chamber temperatures in excess of 1200-1500°F but below 1900-2200°F, where fusion of the residue (clinkering) or fly-ash slagging may occur. In many plants, however, uncontrolled air inleakage results in temperatures which range between 900 and 1300°F. As the refuse burns down and the temperature drops to a level near the minimum end of the range, another batch of refuse is charged to the furnace. The resulting inrush of air cools the primary combustion chamber, quenching the burning of combustible gases and particulates in the primary and secondary combustion chambers. The wide swings in gas temperature under such conditions also cause severe problems in refractory maintenance, and in the generation of steam (where stable pressures and flow rates are necessary). For this latter reason, boilers are seldom installed on batch-fed units.

Most batch-type incinerator units are equipped with forced underfire air fans. These fans pressurize the undergrate plenum, forcing air through the grates and refuse from the windbox below. Overfire air may either be introduced by natural draft through dampered ports in the furnace walls or, in some instances, by fans (preferably separate from the underfire air fans) through air ports near the top of the primary combustion chamber. In at least one plant, improved performance in the burnout of carbon soot from refuse with a high rubber content has been realized using forced overfire air jets in the flue between the primary and secondary chamber.

Flue gases from the primary combustion chamber pass into the secondary chamber, where the combustion of volatile gases and particulates, along with the elimination of noxious odors, is, in theory, completed. To insure complete combusion, temperatures in the secondary chamber should be maintained above 1400°F and sufficient turbulence provided to insure the proper mixing of flue gas and combustion air. Turbulence is often imparted to the gas stream by changing its direction of travel using bridge, checker, or baffle walls. Alternatively, forced secondary air jets can be used to provide this mixing action. In many cases, the combination of buoyant forces which contribute to stratification and inadequate overfire turbulence lead to high combustible content (particulate and gaseous) in the flue gas stream.

Downstream of the secondary chamber, batch-type incinerators have used either a wetted baffle system, cyclone dust collectors or, more commonly, a large settling chamber to capture particulates in the flue gas. For the purposes of the economic analysis, however, we assumed that electrostatic precipitators were used for air pollution control. Other APC devices, however, such as high-energy scrubbers, would be more suitable. We also assumed that an induced draft fan provided the necessary draft to the system. Often, the lack of adequate draft (with natural draft) increases the difficulty of combustion control. A metal stack will be utilized in contrast to the larger masonry stacks employed for natural draft incineration systems.

The residue quality for batch feed units is generally poorer and is more dependent upon operator judgment, motivation, and effort (manual stoking) than for continuous units. In part, this reflects the shorter retention times, deeper refuse beds, and poorer combustion control characteristic of many batch feed designs. However, in most plants, the combustible content of the residue is primarily unburned carbon, rather than biologically active material; but this carbon could constitute 20-30% of that entering with the refuse.

Emissions of combustible particulates and gases are due largely to the inadequate combustion air control and the rapid pyrolysis rate when fresh refuse is charged into a hot furnace. (See Sections VII-C and V.) Mineral particulate emissions tend to be lower for batch units as a consequence of the low undergrate air rates.

b. Advantages and Disadvantages (Section VII-C)

*(1) Advantages.* Batch incineration systems require a relatively modest capital investment relative to other more sophisticated incineration systems and may be designed to accommodate the quantities of refuse characteristic of small towns or municipalities (25 to 100 TPD).

The relative simplicity of design of both the cylindrical and rectangular batch systems allows for straightforward adaptation of furnace size and design to accommodate municipalities with a wide range of incineration needs.

Numerous batch-type incineration systems, both cylindrical and rectangular, of all sizes have been constructed and operated for years. Therefore, the design, engineering, and operating problems associated with such units are well-known. The degree of uncertainty, therefore, associated with the construction and performance of batch units is much lower relative to concepts which have not as yet been so extensively utilized.

*(2) Disadvantages.* Batch feeding results in a cyclic variation in the characteristics of both the refuse bed and the particulate and volatile materials in the primary and secondary chambers. The quantity of combustible materials relative to air supply is also constantly changing. At the time immediately following the charging of refuse, the quantity of combustion air relative to air demand is at its lowest point. Pyrolysis begins to take place immediately upon charging, ignition energy being supplied by radiation from the hot refractory. The concentration of pyrolysis products in the gas phase thus increases to an extent which may very well overwhelm the constant air supply. As a result, a significant quantity of combustible particulates and gases is emitted from the primary and secondary chambers. Although this problem may be reduced by temporarily shutting down the underfire or cone air supply when charging, it is seldom eliminated.

In charging batch systems, refuse feed falls or tumbles directly onto or adjacent to the residue. This creates the possibility of discharging partly incinerated or raw refuse with the residue material. This may be more common with low-capacity (small-diameter) cylindrical systems, where the conical refuse mass deflects the falling charge to the periphery, as opposed to batch rectangular systems, which often have the charging doors located near the rear of the chamber, the incinerated refuse moving toward the front of the furnace. Often, however, fresh refuse may tumble from the rear of the chamber down the inclined grates and mix with the residue.

The rapid combustion upon charging may also result in puffs of smoke and flames being emitted from the charging gate, the stoking doors, or other openings in the furnace, a safety hazard to operating personnel.

Because of the variability in the furnace heat release rate and flue gas characteristics in the primary combustion chamber throughout the burn, less control is maintained over the combustion process relative to continuous systems. This lack of control results in less reliable burnout of combustible materials as well as a greater quantity of particulates and noxious gases leaving the combustion chamber.

Batch systems require somewhat more refractory and grate maintenance than continuous systems, primarily because of the relatively unstable conditions existing in the primary chamber of a batch system. Variations in both the temperature profile in the primary chamber and the nature of the refuse bed result in more rapid spalling of refractory materials and the threat of overheating metal grate parts. Slagging of refractory in the primary and secondary chamber and clinkering on the grates are other causes of high maintenance. The slag adhering to the walls may contribute to the fluxing of refractory materials, as well as the abrasion to any moving parts of the grate systems which may come in direct contact with the slag material.

The residue materials resulting from batch-type incineration systems generally contain a greater degree of putrescibles and unburned (but often devolatilized) combustible materials than those from more modern incineration concepts. Residue (often described as "bonfire ash") is often still burning upon discharge, damaging the grate or grate drive or requiring a reduction in feed rate (capacity).

c. Problem Areas (Section VII-C)

A common problem with most existing batch incinerators is the entrance of surges of cold air through and around the charging gates when refuse is fed to the unit. This cold air lowers the temperature throughout the furnace volume and therefore decreases the burning rate of combustible particulates and noxious gases. The surge of air into the system contributes to the increase in smoke intensity from the stack which often occurs in batch units directly after charging. This flue gas surge also overloads APC systems, causing inefficiency or preventing their use entirely. A more appropriate charging mechanism such as a double gate air seal system or air-tight ram feed system could be utilized to alleviate such problems. The development of reliable, low-silhouette designs for modification of existing plants (space problems) is necessary.

As discussed earlier, most batch incineration systems presently utilize air pollution control systems which are inadequate for meeting the new and more stringent air pollution control regulations now becoming commonplace throughout the country. New, more efficient APC devices, such as medium- and high-energy scrubbers will be necessary for batch units in the future to obtain the high-particulate collection efficiencies required. To minimize the costs of these improved systems, attention to reduction in excess air and stabilization of operation is necessary.

Most batch-fed plants operate with natural draft overfire air. The turbulence resulting from forced overfire air systems would be desirable to improve combustible burnout and to aid in combustion control.

### d. Economics of Batch Feed Incineration Systems

*(1) Capital Investment.* Examination of capital investment data for existing batch incineration systems shows a wide variation in the costs of such facilities. Such variations are attributed to several oftentimes unpredictable variables which include:

- the year of construction;
- the design and capacity of the furnace and related subsystems;
- the aesthetic quality, design, and extent of the building enclosing the incinerator;
- the topography of the land;
- the degree of sophistication of instrumentation and controls;
- geographical variations in labor and materials costs; and
- variations in bidding practices of municipalities.

Data were accumulated for existing batch systems and their investment costs adjusted to reflect labor and materials costs in Boston, Massachusetts, for mid-1969. The appropriate incremental costs for electrostatic precipitators (Section VII.B.), were then included to make up the total investment. Figure VII-19 shows the resulting total plant costs in dollars per ton of rated capacity per 24-hour day as a function of the capacity of the furnace units comprising the plant. The range of probable furnace, building, and electrostatic precipitator costs is shown. The furnace costs include the costs for:

- the crane
- the primary chamber
- the secondary chamber
- forced draft fans
- associated ducting
- residue removal system
- gas cooling system, breeching, and stack
- piping, instrumentation and controls.

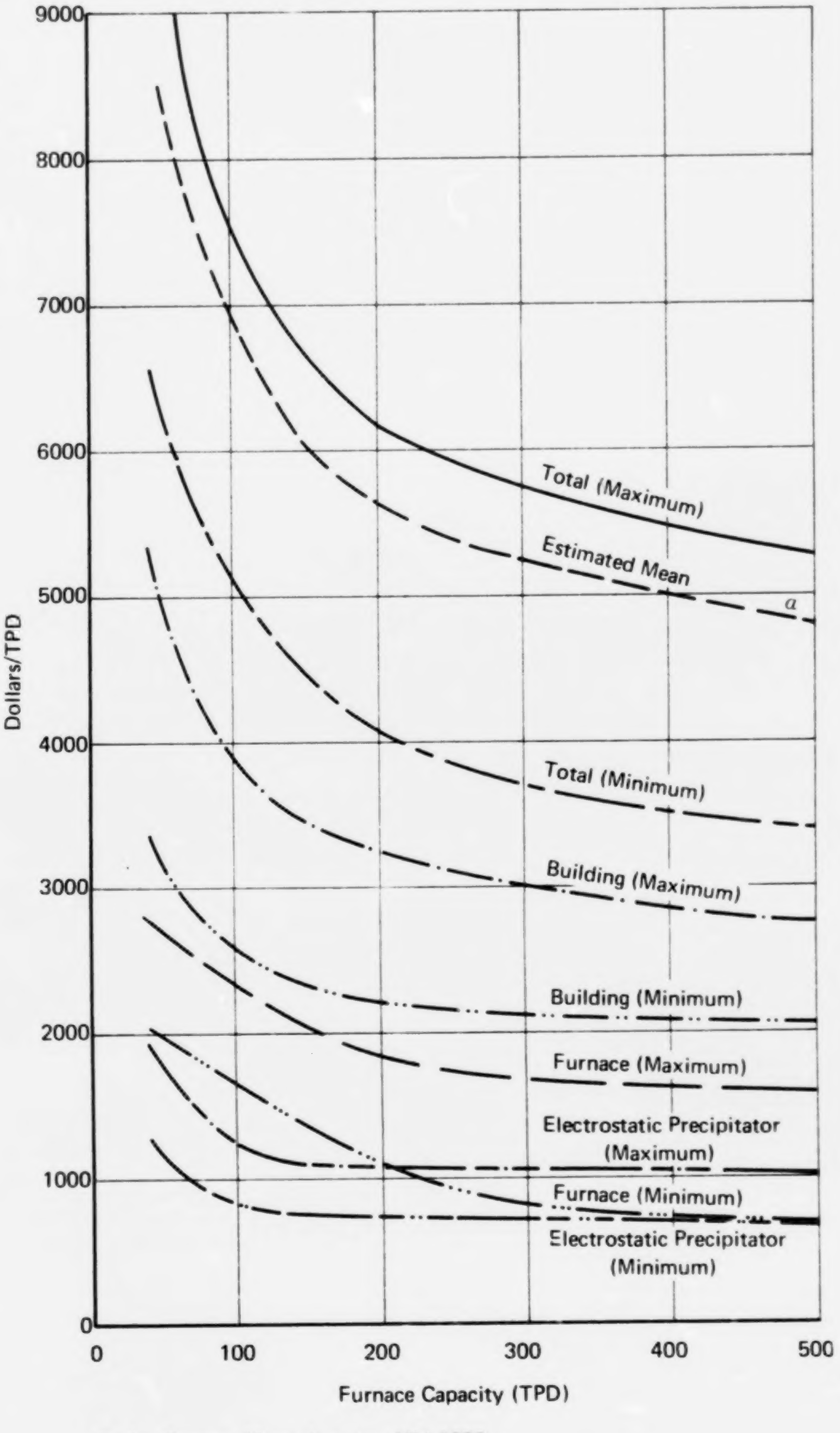
The building costs are comprised of:

- excavation
- land improvements
- foundations
- the refuse pit
- buildings and structural supports
- access roads

The electrostatic precipitator costs include the induced draft fan plus all auxiliaries, motors, and ducting directly associated with the unit.

Figure VII-19 indicates the wide range of batch-feed incinerator costs which presently characterize the incineration industry. For example, an incinerator comprised of 150 ton/day units might generally be expected to cost about $6,000 per ton if built in Boston in mid-1969. However, because of variations in the parameters discussed above, a plant of similar capacity could cost from $4,400 to $6,700 per ton.

As indicated, a significant portion of the variation in total plant costs can be attributed to the variation in building costs. The nature of the building specified may vary from sheet metal siding partially enclosing the facility, to expensive brick buildings totally enclosing the system. Curve "a" shows our estimates for the mean cost of incineration facilities that include brick buildings which enclose offices and associated facilities, the primary and secondary chambers, the residue removal system, and the tipping floor.



**Basis:** Boston, Massachusetts - Mid 1969

FIGURE VII–19 AVERAGE INVESTMENT COSTS: BATCH-FEED SYSTEMS

*(2) Total Operating Costs.* Table VII-24 shows typical total operating costs (including capital charges) for a 400-ton-per-day batch feed incineration plant. The assumed facility has two, 200-TPD units and operates three shifts per day, 250 days per year. The capital investment of $2.3 million was obtained from curve "a" of Figure VII-19.

Unit costs for power, water, operating labor, and supervision were as presented in Section VII.A. Water utilized in this system was assumed to be recirculated except for that used to quench residue materials, that evaporated in the cooling of flue gases down to 600°F and miscellaneous quantities utilized during the operation of the incineration facility. The major use of electricity in the batch incinerator plant is seen to be for the induced draft fans.

Overhead and maintenance costs were developed as a percentage of labor plus supervision and capital investment, respectively. These percentages were based on engineering judgment and review of the limited public information on these costs.

Table VII-24 indicates that the variable costs (i.e., the costs of power and water) contribute approximately 12% of the total operating cost. Labor and maintenance contribute approximately 52%, with amortization and interest on the loan making up the remaining 36% of the operating cost for batch systems.

Figure VII-20 illustrates the effects of rated capacity and the numbers of shifts employed on the total operating costs. The capacities in the horizontal axis, through 600 tons per day, were based on two identical incinerator unit furnaces. Above 600 tons per day, it was assumed that three units were utilized, each of equal capacity. The dotted lines are lines of constant refuse consumption. For example, a 200-TPD incinerator plant operating three shifts per day consumes the same quantity of refuse as does a 300-TPD plant operating two shifts, or a 600 TPD facility operating only one shift. These dotted curves generally indicate that for a defined quantity of refuse consumed, it is more expensive for a municipality to plan a facility for only one-shift operation than for two- or three-shift operation. These curves also indicate that for a constant tonnage of refuse consumed, there do not seem to be significant operating cost differences between two- and three-shift operation, although three-shift operation is more desirable for combustion stability. This results from two counter-balancing effects; as furnace capacity decreases, labor costs increase per unit consumed (the crew size remaining constant); the opposing effect is the decrease in capital charges per unit consumed as capacity decreases.

The curves in Figure VII-20 are based on the assumptions defined above and are presented to illustrate the relative effects of capacity and the number of shifts on the operating costs of batch incineration systems.

## TABLE VII-24

## ESTIMATED COST OF INCINERATION USING BATCH INCINERATION SYSTEMS

**(1969 dollars)**

Reference Location: Boston, Massachusetts, mid-1969
Plant Capacity: 400 TPD (two, 200-TPD furnaces)
Load Factor: 250 days per year; 3 shifts/day
Annual Consumption: 100,000 tons refuse/year
Capital Investment: $2,300,000

| | Units | Dollars/Unit | Units/Ton Refuse Consumed | Dollars/Ton Refuse Consumed |
|---|---|---|---|---|
| **Variable Costs** | | | | |
| Electricity | kwh | $0.015 | 22.3 | 0.33 |
| Water | M Gal | $0.30 | 0.90 | 0.27 |
| | | | | $0.60 |
| **Semi-Variable Costs** | | | | |
| Labor | | | | |
| 1 crane operator per shift @ $5.00/hour | | | | 0.31 |
| 2 furnace operators (stoking & dumping) per shift @ $3.00/hour | | | | 0.38 |
| 1 charging floor man per shift @ $3.00/hour | | | | 0.19 |
| 2 residue removal men per shift @ $3.00/hour | | | | 0.38 |
| 1 supervisor @ $14,000/year | | | | 0.14 |
| 1 weigh scale operator @ $5,500/year | | | | 0.06 |
| | | | | $1.46 |
| Overhead @ 40% of labor & supervision | | | | 0.58 |
| Maintenance and repair @ 2.5% of capital investment annually | | | | 0.58 |
| | | | | $2.62 |
| **Fixed Costs** | | | | |
| Amortization @ 4.7% of capital investment annually | | | | 1.08 |
| Interest on loan @ 3.0% of capital investment annually | | | | 0.69 |
| | | | | $1.77 |
| Total Costs | | | | $4.98 |

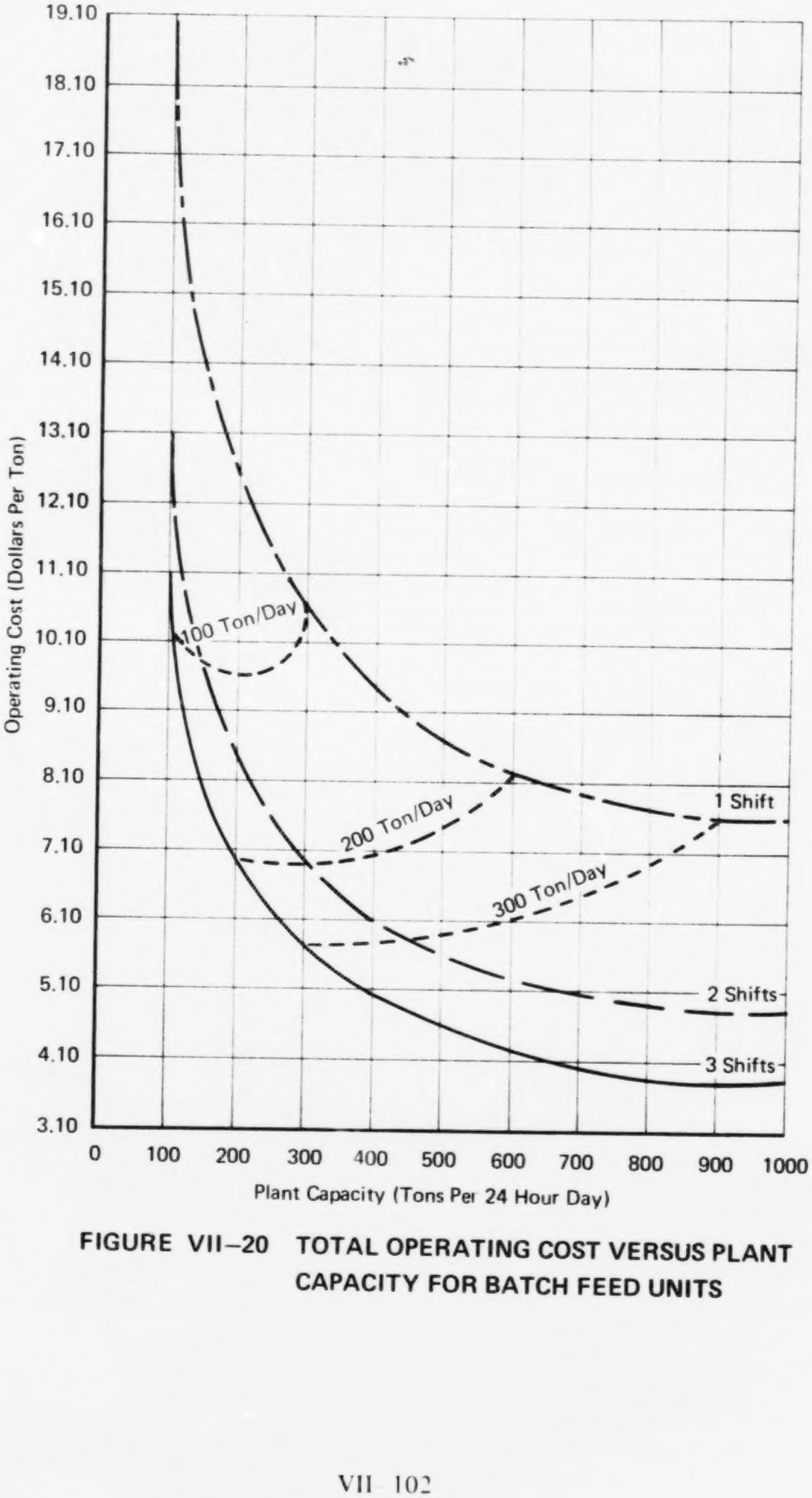


FIGURE VII–20 TOTAL OPERATING COST VERSUS PLANT CAPACITY FOR BATCH FEED UNITS

Table VII-25 indicates the percent contribution of the various component costs comprising the total operating costs in Figure VII-20. These percentages were developed for three different rated plant capacities and for one-, two-, and three-shift operation. These percentages allow for the modification of costs appearing in Figure VII-20 to reflect assumptions other than those used to develop these component costs.

### TABLE VII-25

### DISTRIBUTION OF TOTAL OPERATING COSTS FOR BATCH FEED INCINERATOR SYSTEMS
(%)

| Plant Capacity | 100 TPD | | | 500 TPD | | | 900 TPD | | |
|---|---|---|---|---|---|---|---|---|---|
| Shifts/Day | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| **Cost** | | | | | | | | | |
| Power | 2 | 3 | 3 | 4 | 6 | 7 | 4 | 7 | 9 |
| Water | 1 | 2 | 2 | 3 | 5 | 6 | 4 | 6 | 7 |
| Labor and Overhead | 49 | 58 | 63 | 24 | 32 | 37 | 18 | 25 | 29 |
| Maintenance | 7 | 7 | 8 | 10 | 11 | 12 | 10 | 13 | 13 |
| Capital Charges | 41 | 30 | 24 | 59 | 46 | 38 | 64 | 49 | 42 |
| Total | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

## 5. Continuous Feed Systems: Rectangular Construction

### a. Process Description

Rectangular continuous feed incinerator systems may be characterized by the type of grate system employed. Three types are prevalent: the traveling grate, the reciprocating or pusher grate, and the rocking grate. A discussion and description of each of these grate systems is provided in part B of Appendix H, and, therefore, will not be repeated here.

Refuse is generally fed by crane from a receiving and storage pit to the charging hopper, moving by gravity down the feed chute and into the primary combustion chamber as material is drawn from the bottom by the grate action. The refuse in the feed chute serves as a seal preventing the gases in the primary combustion chamber from passing up through the chute to the charging floor. In the primary chamber, entering refuse is ignited by the burning refuse and by radiation from the hot refractory, and burned, with the noncombustible residue remaining on the grates. Siftings (fine material which passes through the grate openings) are removed manually, or with a water sluice, or by a screw or drag conveyor operating beneath the grates, and are discharged to the residue removal system.

The walls, roof, and/or arches in the primary combustion chamber are generally constructed of suspended refractory firebrick, although castable and preburned refractory have been used for sprung arches and for patching. Air-cooled silicon carbide blocks have been increasingly used for wall construction near the grate line to alleviate localized slagging and abrasion problems which interfere with continuous furnace operation. Insulating firebrick may also be employed behind the dense refractory to minimize outside wall temperatures (vital for totally housed furnaces).

Gas temperatures in the primary combustion chamber may range from 1500 to 2500°F depending upon the heating value of the refuse, the intensity of overfire mixing, and the percent excess air utilized. All continuous units employ underfire air which enters the primary chamber from an undergrate windbox, passing through the grates and through the refuse bed. In many units, the underfire air windbox is partitioned to control the distribution of air along the grate (none at the feed end, little at the discharge end). Forced overfire air is also utilized, and as the underfire air, may be adjusted to control the quantity and distribution of combustion air throughout the furnace. Depending upon the design of the forced overfire air jet nozzles and their location in the primary furnace, localized temperatures as high as 2800°F may result, primarily due to insufficient mixing of the flue gases in the primary chamber.

The combustion of volatile gases and particulates and the elimination of noxious odors is often completed in a secondary combustion chamber. In units operating without such chambers, the need for overfire air jet induced turbulence is greatly increased. To insure complete combustion, temperatures in the secondary chamber must be maintained above 1400°F and sufficient turbulence provided to insure the proper mixing of flue gas and combustion air. Turbulence is imparted to the gas stream either by changing the direction of travel through the use of bridge, checker, or baffle walls or by utilizing forced secondary air jet nozzles to provide this mixing action.

Downstream of the secondary chamber, many continuous incinerators use wide-spaced wetted transverse wall baffles or close-spaced wetted multiple impingement baffles to capture particulates in the flue gas. The design of these systems varies considerably, but none appear to be able to control particulate emissions at the more stringent levels already required in many areas.

The residue leaving the primary combustion chamber may either fall directly into a dry ash pit or hopper which is emptied periodically or, more commonly, it may fall into a water-filled quench tank equipped with a residue conveyor system. The water in this tank serves as an air seal, permitting residue removal without disruption of furnace draft. As with most incinerators, residue quality is importantly related to judgments made by the operators and to refuse composition. The stability of temperatures and air supply and the ability to modulate underfire and overfire air (tailoring the combustion environment along the grate to the needs of the refuse bed) gives continuous feed units the capability to produce high-quality residue.

The air pollution problems of continuous feed incinerators are more associated with mineral particulate than with combustibles, although the latter are still important. Existing APC systems can readily control mineral particulate. Combustible pollutant control is also possible with improved operating practices (see Section VII-C and Chapter V).

b. Advantages and Disadvantages

*(1) Advantages.* Numerous continuous systems of the type being considered here have been constructed. Therefore, the design, engineering and operating problems associated with such units are well-known. The technical risk in building such systems will thus be lower relative to concepts which have not as yet been as extensively utilized. A great deal, however, remains to be understood regarding such systems to permit optimum designs and more assured superior performance.

Continuous systems are well-suited to controlled combustion of refuse. This can result in better residue quality and less combustible particulates and noxious gases leaving the combustion furnaces.

Continuous systems of the type being considered here avoid mixing residue with raw refuse feed, a common problem for batch systems.

Continuous incineration systems can provide flue gases which are better suited than those from batch feed systems for treatment with APC devices downstream. In addition to providing better burnout of combustible particulate and gases, continuous systems provide a steady flow of flue gas to the APC device in contrast to the variable-flow rates, temperatures, and other characteristics of the flue gas for batch-type units.

Well-operated continuous systems require less refractory and grate maintenance relative to batch systems. This decrease in maintenance is attributed to the more stable conditions existing in the primary chamber of continuous systems as opposed to the wide variations in both temperature and the characteristics of the refuse bed and combustion gases which are common in batch feed systems.

*(2) Disadvantages.* Although continuous feed rectangular construction incineration systems are an improvement over batch-type systems, there is still much room for further advancement. Alterations in the design of continuous systems as well as the development of new advanced incineration concepts will improve incineration performance. The following paragraphs indicate those areas where improvement is most necessary:

> The residue material resulting from conventional continuous systems generally still contains putrescibles and combustible materials. Unburned material can result from poor operating practices, but often it reflects the inability of conventional systems to adequately dry and burn high-moisture refuse (e.g., fruits). Increasing the residence time to assure burnout, however, may disadvantageously affect plant capacity.
>
> Almost all contemporary grate systems are susceptible to undergrate burning, which can cause grate and windbox damage or plant shutdown. Burning under the grate is caused by flow and subsequent ignition of combustible fluids such as fats, oils, paint, melted aluminum, etc. (or siftings), through the grate. Grate systems with small grate openings are, therefore, less susceptible to these problems.
>
> Grate and grate drive maintenance is an important part of total plant maintenance costs (although less important than refractory maintenance). Reciprocating and rocking grate maintenance requires shutdown and cooling of the furnace before repairs can be made, resulting, often, in decreased plant availability. Traveling grate systems can often receive minor repairs without shutdown.
>
> Continuous systems, in comparison to batch systems, are more costly to build (10 to 15% higher) and to operate (5 to 10% higher). In general, however, much better performance as regards the five performance criteria is assured.

c. Problem Areas (Section VII-C)

Associated with many existing continuous incineration systems are air pollution control devices comprised of wetted baffle walls which act as "fly paper" to trap the larger particles suspended in the flue gas stream. This type of air pollution control, however, is not capable of meeting the more stringent air pollution control regulations now becoming commonplace throughout the country. More efficient APC devices, such as electrostatic precipitators, high-energy scrubbers, or baghouses are necessary to obtain the high collection efficiencies required.

The continuous residue handling system often associated with continuous systems requires intensive maintenance and operator attention to avoid plant downtime. The flight conveyors which drag the residue from the quench tank often become entangled or jammed with wire, pipes, and other such residue, making the system inoperable or damaging the conveyor or conveyor drive. Corrosion and abrasion of metal parts is another common problem.

Although over 100 incinerators of this type have been built, the great variability in design between various plants suggests that no well-established design principles have been developed. Some plants adequately fulfill the five performance criteria. However, even the acceptable plants could undoubtedly produce better residue, demand less of the APC system to meet present or future emission codes, and demand less of municipal financial resources. To supply these design principles, engineering evaluation of such systems, including experimental tests, will be required.

Automatic combustion control is more attainable in continuous than in batch feed units. To have control which can cope with refuse heterogeneity, however, new instrumentation and control systems must be developed and tested. Engineering evaluations will be a valuable resource to such development.

### d. Economics of Continuous Feed, Rectangular Construction Incineration Systems

*(1) Capital Investment.* Examination of the unit costs ($/TPD) of existing continuous incineration systems and recent bids on proposed continuous incineration units shows a wide variation in the investment for such plants. Several variables (presented above for batch feed systems) contribute to the wide range shown for the data.

Data were accumulated for continuous systems either existing or proposed. Their capital costs were then adjusted to reflect construction, labor, and materials costs for Boston, Massachusetts, in mid-1969. The appropriate incremental costs for electrostatic precipitators (Section VII-B) were then included to make up the total investment. Figure VII-21 shows these total plant costs in dollars per ton of rated capacity per 24-hour day as a function of the capacity of the furnace units comprising the plant. The range of probable building, furnace, and electrostatic precipitator costs is also shown. The building and furnace costs include the same cost categories as the batch units.

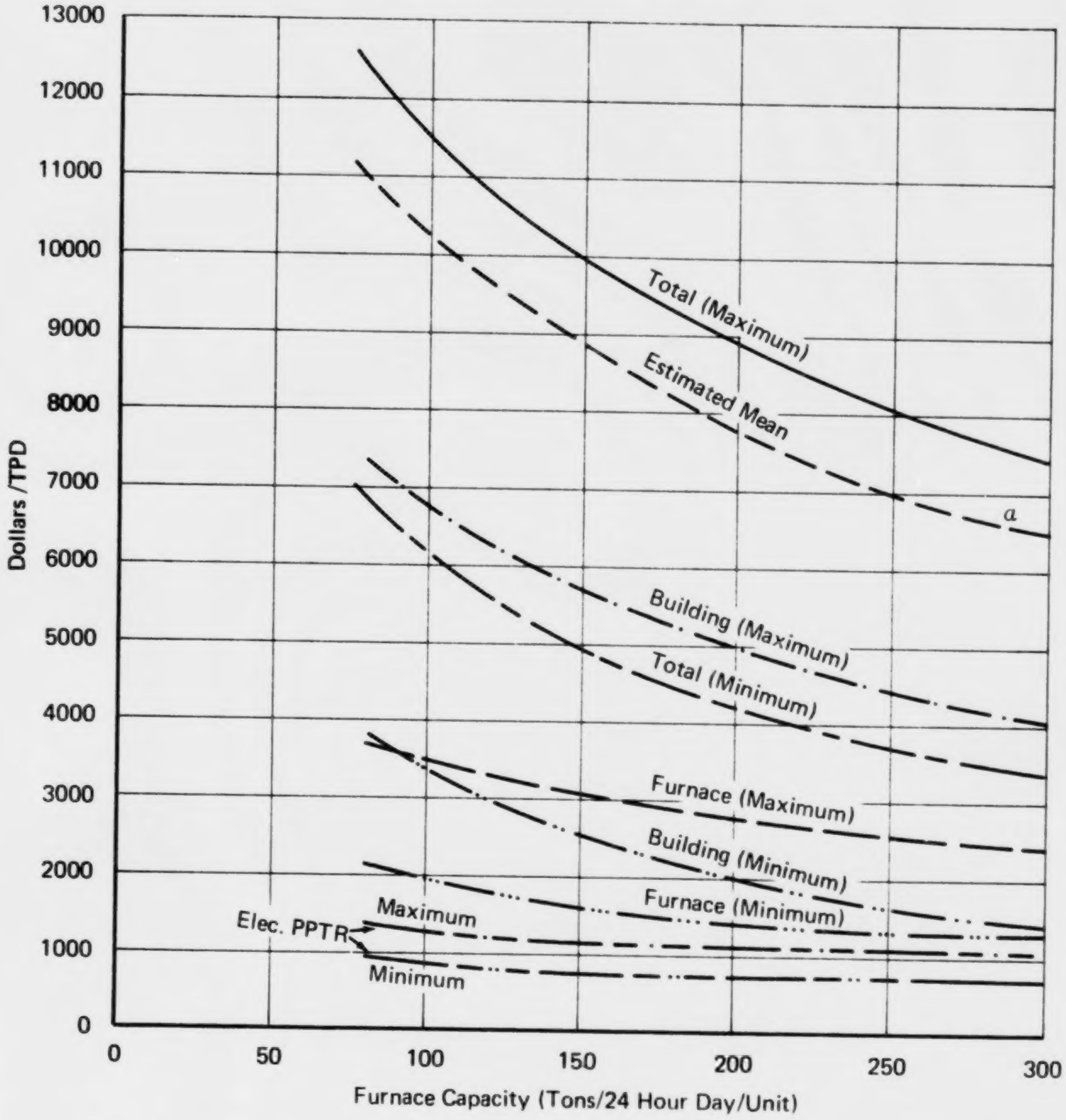


**FIGURE VII–21** AVERAGE INVESTMENT COSTS: CONTINUOUS FEED SYSTEMS RECTANGULAR CONSTRUCTION

Figure VII-21 indicates the wide range of continuous feed incinerator costs which presently characterize the incineration construction industry. For example, an incinerator comprised of 150-TPD units might generally be expected to cost approximately $8,900 per TPD if built in Boston in mid 1969. However, because of the variations in parameters, a plant of similar capacity could cost from $4,900 to $9,900 per ton of daily capacity.

As Figure VII-21 indicates, the variation in incinerator costs can be mainly attributed to the variation in costs of buildings. The building may vary from sheet metal siding partially enclosing the facility to expensive brick totally enclosing the system. Curve "a" reflects our estimates for the mean cost of typical incinerator facilities, including brick buildings which enclose offices and associated facilities, the furnace system, the pit and truck dumping area.

*(2) Total Operating Costs.* Table VII-26 shows typical operating costs for a 400-TPD contemporary continuous feed incineration facility. The facility has two, 200-TPD units and operates three shifts per day, 250 days per year. The capital investment figure of $3,100,000 was obtained from curve "a" of Figure VII-21.

Unit costs for power, water, operating labor, and supervision were as presented in Section VII-A. Water utilized in the system was assumed to be recirculated except for small quantities of make-up water, the amounts evaporated in the cooling of flue gases to 600°F, and miscellaneous quantities used during plant operation. The majority of the electricity is consumed in the operation of the induced draft and forced air fans.

Overhead and maintenance costs were developed as a percentage of labor plus supervision and capital investment, respectively. These percentages were based on engineering judgment and review of the limited public information on these costs.

Table VII-26 indicates that the variable costs (power and water) contribute approximately 10% to the total operating cost. Labor and maintenance contribute approximately 47%, with amortization and interest on the loan making up the remaining 43% of the operating costs for continuous systems.

Figure VII-22 illustrates the effects of rated capacity and the number of shifts employed on the total operating costs. The plant capacities on the horizontal axis were based on two identical incinerator furnaces. The dotted lines are lines of constant refuse consumption.

## TABLE VII-26

## ESTIMATED COST OF INCINERATION FOR RECTANGULAR CONTINUOUS GRATE INCINERATION SYSTEMS
(1969 dollars)

Reference Location: Boston, Massachusetts, mid-1969
Plant Capacity: 400 TPD (two, 200-TPD furnaces)
Load Factor: 250 days per year; 3 shifts per day
Annual Consumption: 100,000 tons refuse/year
Capital Investment: $3,100,000

| | Units | Dollars/Unit | Units/Ton Refuse Consumed | Dollars/Ton Refuse Consumed |
|---|---|---|---|---|
| **Variable Costs** | | | | |
| Electricity | kwh | $0.015 | 22.3 | 0.33 |
| Water | M Gal | $0.30 | 0.90 | 0.27 |
| | | | | $0.60 |
| **Semi-Variable Costs** | | | | |
| Labor | | | | |
| 1 crane operator per shift @ $5.00/hour | | | | 0.31 |
| 1 furnace operator per shift @ $5.00/hour | | | | 0.31 |
| 1 charging floor man per shift @ $3.00/hour | | | | 0.19 |
| 2 residue men per shift @ $3.00/hour | | | | 0.38 |
| 1 supervisor @ $14,000/year | | | | 0.14 |
| 1 weigh scale operator @ $5,500/year | | | | 0.06 |
| | | | | $1.39 |
| Overhead @ 40% of labor & supervision | | | | 0.56 |
| Maintenance and repairs @ 2.5% of capital investment annually | | | | 0.78 |
| | | | | $2.73 |
| **Fixed Costs** | | | | |
| Amortization @ 4.9% of capital investment annually | | | | 1.52 |
| Interest on loan @ 3.0% of capital investment annually | | | | 0.93 |
| | | | | $2.45 |
| Total Costs | | | | $5.78 |

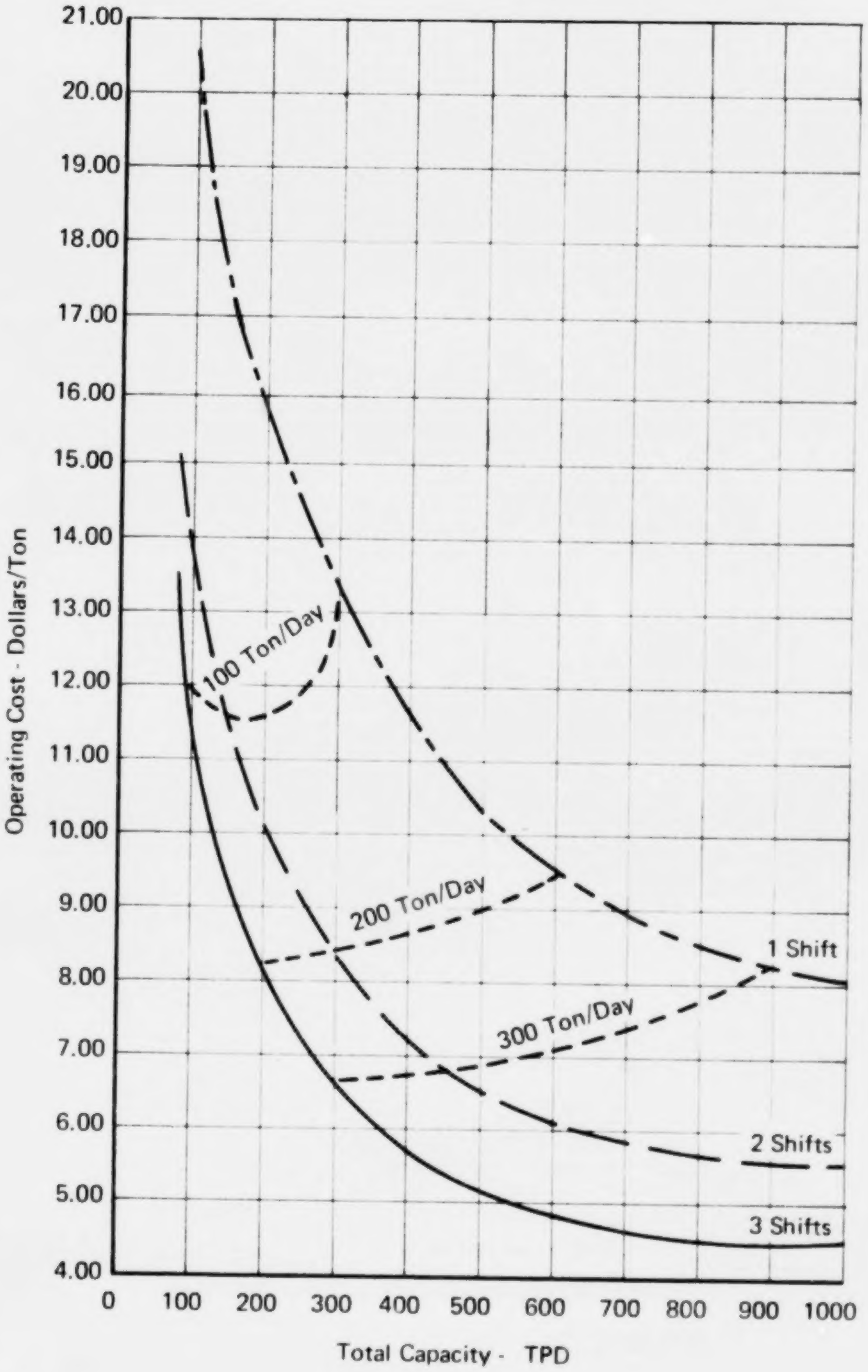


FIGURE VII–22 TOTAL OPERATING COST VS. PLANT CAPACITY FOR CONTINUOUS FEED, RECTANGULAR CONSTRUCTION UNITS

Table VII-27 indicates the contribution of the various components comprising the total operating costs in Figure VII-22. These percentages were developed for three different rated plant capacities, for one-, two- and a three-shift operation. These percentages allow for the modification of costs appearing in Figure VII-22 (as discussed in Section VII-A) to reflect assumptions other than those used to develop these component costs.

### TABLE VII-27

### DISTRIBUTION OF TOTAL OPERATING COSTS FOR CONTINUOUS FEED SYSTEMS – RECTANGULAR CONSTRUCTION

(%)

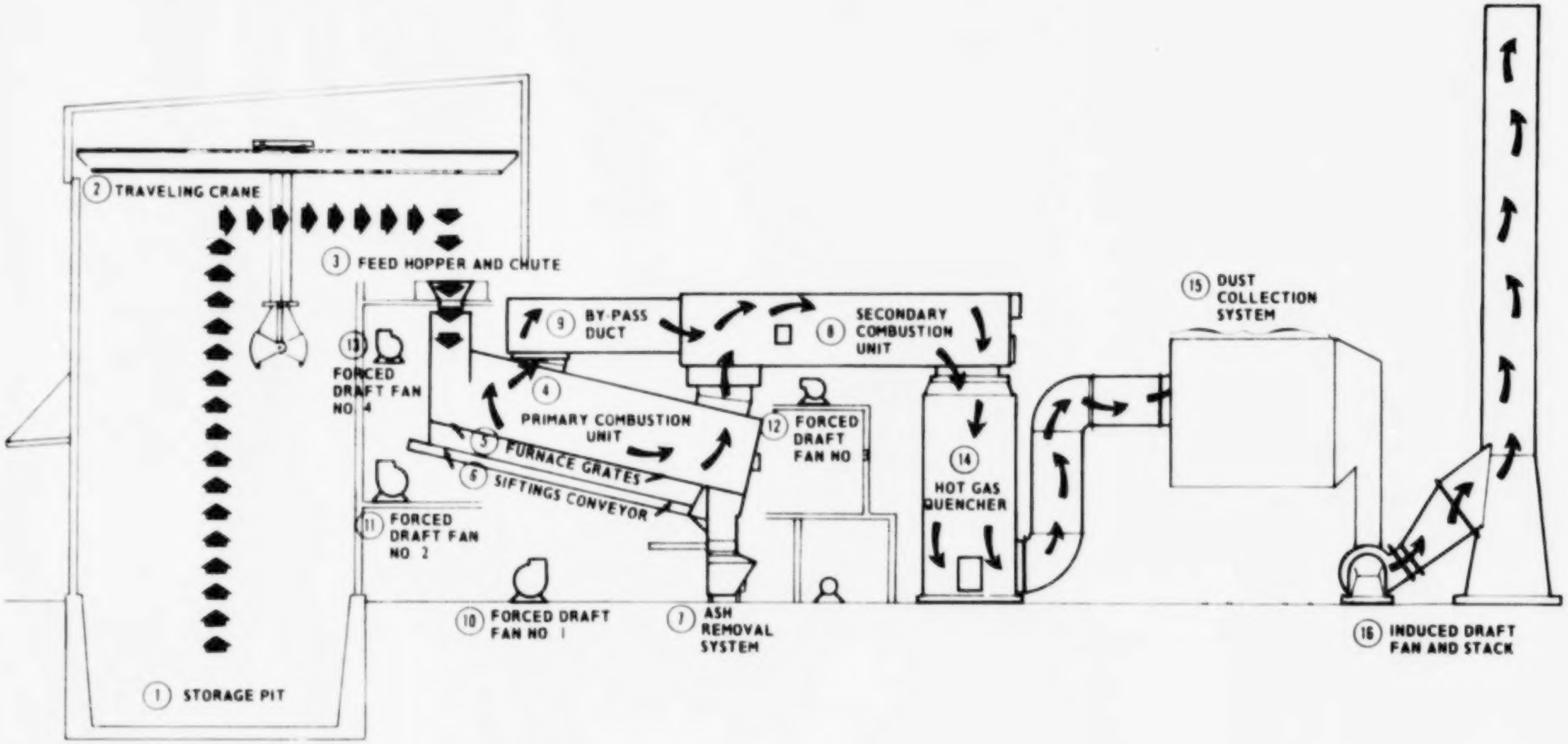
| **Plant Capacity** | 100 TPD | | | 600 TPD | | | 900 TPD | | |
|---|---|---|---|---|---|---|---|---|---|
| **Shifts/Day** | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| **Cost** | | | | | | | | | |
| Power | 2 | 2 | 3 | 3 | 6 | 7 | 4 | 6 | 8 |
| Water | 1 | 2 | 2 | 3 | 5 | 6 | 3 | 5 | 6 |
| Labor and Overhead | 43 | 53 | 58 | 19 | 26 | 31 | 15 | 21 | 25 |
| Maintenance | 7 | 8 | 9 | 10 | 12 | 14 | 11 | 13 | 15 |
| Capital Charges | 47 | 35 | 28 | 65 | 51 | 42 | 67 | 55 | 46 |
| Total | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

6. Continuous Feed Systems: Horizontal Cylindrical Construction

a. Process Description (Section IV-B)

Figure VII-23 schematically compares the features of the horizontal cylindrical unit with those of the conventional rectangular continuous systems. The primary chamber is a horizontal cylindrical unit which has an air-cooled and air-tight steel shell and a refractory brick lining. This particular furnace system, as offered by North American Incinerator Corporation (NAIC), has a capacity of 225 tons per day and employs four mechanical rocking grate sections, each 8 feet wide and 11 feet long.

As in many continuous feed plants, specially designed zones in the underfire air windbox distribute air through the burning refuse. In addition, however, forced overfire air enters the furnace tangentially along both sides of the grate.



① STORAGE PIT
② TRAVELING CRANE
③ FEED HOPPER AND CHUTE
④ PRIMARY COMBUSTION UNIT
⑤ FURNACE GRATES
⑥ SIFTINGS CONVEYOR
⑦ ASH REMOVAL SYSTEM
⑧ SECONDARY COMBUSTION UNIT
⑨ BY-PASS DUCT
⑩ FORCED DRAFT FAN NO 1
⑪ FORCED DRAFT FAN NO 2
⑫ FORCED DRAFT FAN NO 3
⑬ FORCED DRAFT FAN NO 4
⑭ HOT GAS QUENCHER
⑮ DUST COLLECTION SYSTEM
⑯ INDUCED DRAFT FAN AND STACK

FIGURE VII–23 SCHEMATIC OF CONTINUOUS FEED, HORIZONTAL CYLINDRICAL CONSTRUCTION INCINERATION SYSTEM

This air provides overfire turbulence, furnace wall cooling (minimizing slag adhesion), and preheats the air supply for more efficient combustion.

Siftings are continually moved by a heavy-duty, slow-moving drag conveyor to the ash removal system. Siftings, along with the residue from the grates, falls directly into a container-type or continuous conveyor-type residue handling system.

The secondary chamber provides a high-temperature environment of 1600-2000°F for the complete combustion of particulates and gases. The secondary furnace, like the primary chamber, will employ a horizontal cylindrical air-cooled steel shell lined with standard firebrick refractory. The tangential inlet forced air which is utilized for wall cooling is independently controlled and enters the secondary chamber through specially designed air ports. This incoming air will cool the refractory wall and promote turbulence. An emergency flue gas outlet will be provided at the end of the secondary chamber to safely release hot gases in the event of a power failure or other emergency which stops the induced draft fan.

As Figure VII-23 indicates, a by-pass duct is also provided to promote the flow of hot combustion gases to the feed end of the primary furnace. The hot gases aid in drying the incoming refuse and cause more rapid ignition of the refuse. The by-pass duct provides a second outlet for the primary chamber, which tends to reduce the gas velocity over the discharge grate. This will reduce the pick-up and carry-over of fly ash particles and improve the cleanliness of the effluent gases. In addition, the by-pass duct adds furnace volume (about 1500 cubic feet) for burn-out of combustibles. The construction and air supply system of this duct is identical to that of the secondary combustion chamber. An axial inspirator-type air jet has been provided at the entrance to the by-pass duct to control the quantity of gas which flows through this chamber. A separate high-pressure fan has been provided to supply the air to this inspirator.

The flue gases leaving the secondary furnace will be at a temperature between 1600°F and 2000°F. To avoid rapid oxidative corrosion of steel equipment and structures downstream of the secondary chamber, it is necessary to cool the hot flue gases to about 600°F with a water spray. The fine atomizing spray devices have been designed such that the light gauge stainless steel quencher will operate with a dry bottom, thus avoiding severe corrosion and sewer problems.

Following the quencher would be an appropriate air pollution control device, an induced draft fan and steel stack. For the economic analysis to follow, an electrostatic precipitator will be considered as the air pollution control device.

The comments regarding residue quality presented for continuous feed, rectangular construction are applicable to the horizontal cylindrical construction system. Regarding air pollution, one may speculate that the increased combustion air control and intense overfire air jet induced turbulence throughout NAIC-type systems may provide superior burn-out of combustible pollutants. Mineral particulate loadings, however, should be similar to those for continuous feed rectangular furnaces with similar grate systems.

b. Advantages and Disadvantages

*(1) Advantages.* The air-tight steel encasement of the unit eliminates air leaks prevalent in many existing systems and thus aids in controlling combustion air.

The cylindrical design with thin air-cooled self-supporting refractory walls is generally less expensive than the suspended wall refractory construction used in rectangular units.

The installation of these incinerators is less expensive because the furnaces are self-supporting and can be built before or during the construction of the housing.

(See also Section VII-D.5.b(1))

*(2) Disadvantages.* This system has not been tested on a commercial scale; therefore, problems may arise in the start-up of new systems. The basic design and operating principles, however, have been shown to be effective in industrial applications.

Insulating fire brick is not utilized for most of the combustion chamber wall area in the NAIC design. Thus, the outer steel walls of the primary and secondary chamber will be very hot (about 600°F) and consequently present a safety hazard to operating personnel. Operation of this system would, therefore, require rigid safety precautions to counter this hazard.

The system was designed so that much of the plant would not be enclosed by a building. Although this design has some economic advantages, it is aesthetically less desirable than totally enclosed units. Additional enclosures for this system would add 10 to 20% to the building and structural costs for the facility and would require some modification to the design.

### c. Identification of Problem Areas

The horizontal cylindrical furnace design is untried in incinerator application although used widely in the chemical process industries. Because of the wide applications of these designs, however, no unsolvable problems will be encountered.

The overfire air system and combustion control concept for this design are untried. Although no problems are evident, demonstration of these concepts is necessary. Slag accumulation, interfering with overfire air jet performance, for example, could significantly affect refractory maintenance and furnace combustion characteristics.

### d. Economics of Continuous Feed Horizontal Cylindrical Construction Incineration Systems

*(1) Capital Investment.* The horizontal cylindrical furnace is being offered by NAIC as 225-TPD furnace units, although furnaces of different capacities could be designed and constructed. We estimate that the total cost for an incineration facility comprised of two, 225-TPD furnaces and associated subsystems would be approximately $2,200,000 (for Boston, Mass., mid-1969). This incineration concept was designed to incorporate a building which encloses only a limited section of the system. This has economic advantages but may detract from the aesthetic quality of the facility. A building enclosing a greater portion of the system could add as much as $2,000 per ton of capacity (an increase of $900,000) to the investment costs. Simple screening of the plant would be 5 to 10 times less costly. These costs are ADL estimates, however, and do not reflect the policy or guarantees of NAIC.

*(2) Total Operating Costs.* Table VII-28 was developed to illustrate the "typical" operating costs for a 450-TPD incineration facility comprised of two, 225-TPD NAIC-type furnaces. For this purpose, it was assumed that the facility will operate three shifts per day for 250 days a year.

The unit costs for power, water, operating labor and supervision were as presented in Section VII.A. Overhead and maintenance costs were expressed as a percentage of labor plus supervision and capital investment respectively. These percentages were based on engineering judgment and analysis of this particular incinerator concept and data for other continuous incineration systems.

Table VII-28 shows that the variable costs (power and water) contribute approximately 13% to the total operating cost. Labor and maintenance contribute approximately 50% with the amortization and interest on the loan making up the remaining 37% of the operating costs for these types of systems.

## TABLE VII-28

## ESTIMATED COSTS OF INCINERATION FOR CONTINUOUS FEED, HORIZONTAL CYLINDRICAL CONSTRUCTION

(1969 dollars)

Reference Location: Boston, Massachusetts, mid-1969
Plant Capacity: 450 TPD (two, 225-TPD furnaces)
Load Factor: 250 days per year; 3 shifts per day
Annual Consumption: 112,500 tons refuse/year
Capital Investment: $2,200,000

| | Units | Dollars/Unit | Units/Ton Refuse Consumed | Dollars/Ton Refuse Consumed |
|---|---|---|---|---|
| **Variable Costs** | | | | |
| Electricity | kwh | $0.015 | 22.3 | 0.33 |
| Water | M Gal | $0.30 | 0.90 | 0.27 |
| | | | | $0.60 |
| **Semi-Variable Costs** | | | | |
| Labor | | | | |
| 1 crane operator per shift @ $5.00/hour | | | | 0.28 |
| 1 furnace operator per shift @ $5.00/hour | | | | 0.28 |
| 1 charging floor man per shift @ $3.00/hour | | | | 0.17 |
| 2 residue men per shift @ $3.00/hour | | | | 0.33 |
| 1 supervisor @ $14,000/year | | | | 0.12 |
| 1 weigh scale operator @ $5,500/year | | | | 0.05 |
| | | | | $1.23 |
| Overhead @ 40% of labor & supervision | | | | 0.49 |
| Maintenance and repair @ 2.5% of capital investment annually | | | | 0.50 |
| | | | | $2.22 |
| **Fixed Costs** | | | | |
| Amortization @ 5.4% of capital investment annually | | | | 1.06 |
| Interest on loan @ 3.0% of capital investment annually | | | | 0.59 |
| | | | | $1.65 |
| Total Costs | | | | $4.47 |

Figure VII-24 shows the effects of rated capacity and the number of shifts employed on the operating costs of horizontal cylindrical continuous systems. The capacities on the horizontal axis were based on multiples of a 225-TPD furnace. These costs are ADL estimates, however, and do not reflect the policy or guarantees of NAIC.

Table VII-29 indicates the contribution of the various component costs comprising the total operating costs in Figure VII-24. These percentages, developed for three different rated plant capacities for one-, two- and three-shift operation, allow for the modification of costs appearing in Figure VII-24 (as discussed in the Introduction to Section VII) to reflect assumptions other than those used to develop these component costs.

### TABLE VII-29

### DISTRIBUTION OF TOTAL OPERATING COSTS FOR A CONTINUOUS FEED, HORIZONTAL CYLINDRICAL INCINERATOR SYSTEM

(%)

| **Plant Capacity** | **225 TPD** | | | **450 TPD** | | | **675 TPD** | | |
|---|---|---|---|---|---|---|---|---|---|
| **Shifts/Day** | **1** | **2** | **3** | **1** | **2** | **3** | **1** | **2** | **3** |
| **Cost** | | | | | | | | | |
| Power | 3 | 5 | 6 | 4 | 6 | 7 | 4 | 7 | 8 |
| Water | 3 | 4 | 5 | 3 | 5 | 6 | 4 | 6 | 7 |
| Labor and Overhead | 37 | 45 | 50 | 26 | 34 | 39 | 21 | 28 | 33 |
| Maintenance | 7 | 9 | 9 | 9 | 10 | 11 | 9 | 11 | 12 |
| Capital Charges | 50 | 37 | 30 | 58 | 45 | 37 | 62 | 48 | 40 |
| Total | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

### 7. Continuous Feed Systems: Ignition Grate Plus Burnout Kiln Construction

a. Process Description (see also Appendix H)

The ignition grate plus burnout kiln system utilizes one or more grate sections (typically two) to dry and ignite the refuse and a short rotary kiln section in which to complete combustion. The feed system for this design concept is

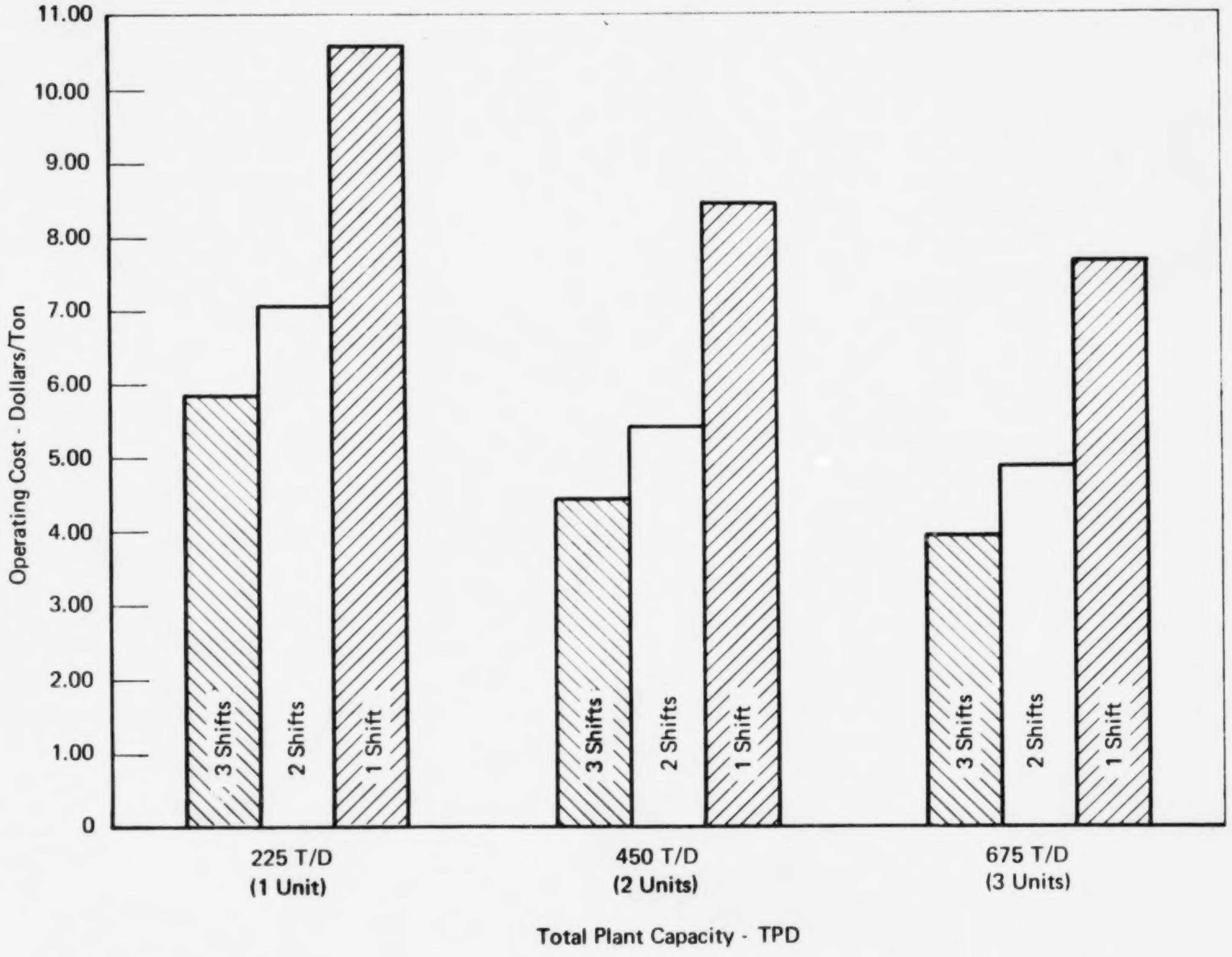


FIGURE VII–24 TOTAL OPERATING COST FOR CONTINUOUS FEED, HORIZONTAL CYLINDRICAL CONSTRUCTION INCINERATOR SYSTEMS

typical of most existing continuous plants. Refuse from the drying grate drops approximately eight feet to the ignition grate to tumble and break up the refuse. The mechanically operated drying and ignition grates both have variable speeds which can be controlled to suit the desired rates of combustion. Grate type and drop heights vary considerably.

Underfire air, preheated by cooling sections of the refractory walls in the ignition chamber, enters through the ignition grates. Siftings from the drying and ignition grate sections are continually removed by screw conveyors. The screw conveyor collecting siftings from the drying grates transports these siftings to the ignition grate section, whereas siftings from the ignition grate are collected and transported directly to the ash residue hopper or continuous residue conveying system.

The partially burned refuse is discharged from the ignition grate section into a slowly revolving inclined rotary kiln. The speed of this kiln is variable to suit the desired conditions. The kiln is lined with 9″ refractory kiln blocks and 2″ insulating blocks. For a 300 TPD furnace, the kiln is typically 30′ long with an outside diameter of about 12-1/2 feet. The slow tumbling action of the refuse as it passes through the kiln continually exposes unburned refuse to the high-temperature gases from the ignition grates, whereby incineration is completed. Cans are crushed as the load in the kiln spills over. About 50-60% of the burning takes place in the ignition chamber and 40-50% in the kiln. A kiln of the preceding dimensions has a burning area of approximately 350 square feet.

A portion of the flue gases from the ignition chamber travels through the kiln and into a mixing chamber. The remainder of the hot gases from the ignition chamber flow through a by-pass duct located above the kiln to the mixing chamber. The flue gas leaving the mixing chamber may either be directed directly to the gas conditioning and air pollution control units and thence to the stack, or be passed through a waste heat boiler and thence to the APC system stack. For the following analyses, we will assume that an electrostatic precipitator is utilized as the air pollution control device and that *no* waste heat boiler is employed. The flue gases will be cooled to 600°F by passing through a spray chamber prior to entering the precipitator.

A furnace system similar to the one discussed above is offered by International Incinerators, Inc., based on a design licensed from the Volund Company of Denmark.

The residue quality for furnaces of this type, while subject to operator errors, is generally superior or equal to that of most existing continuous feed plants. This undoubtedly reflects the tumbling action between the grates and in the kiln. In regard to air pollution, the grate kiln system appears to show higher-than-average mineral particulate loadings and slightly lower amounts of combustible pollutants. The former probably results from attrition of ash residue in tumbling with subsequent entrainment. Lower combustible pollutant emissions may reflect somewhat hotter overfire mixing and a more evenly distributed release of volatile matter.

### b. Advantages and Disadvantages

*(1) Advantages.* The unique action within the kiln effectively exposes unburned refuse surfaces to the hot flue gas stream. The high residue quality which results suggests that the form or intensity of agitation provided by a rotary kiln is superior to that obtained with conventional continuous grate systems.

The rotary kiln chamber provides additional residence time for efficient residue burnout to take place. The rotational speed of the kiln can be varied to adjust the residence time as the nature of the refuse dictates to provide adequate time for burnout to take place.

A distinct advantage of the system is the efficient volume reduction of the residue material. This is attributed not only to the excellent burnout of combustible material in the residue but also to the fact that action of the kiln crushes and breaks the bottles, cans and other larger components of the residue, increasing the residue bulk density.

The kiln section of the furnace is grateless. This, naturally, avoids the operating and maintenance problems with the portion of the grate system (the discharge end) replaced by the kiln. Kiln refractory and drive maintenance, however, are incurred. Also, the problems associated with the melting and fusion of plastics, metals, and other such refuse components on the ignition and drying grates are not eliminated with the kiln system as these tend to be most troublesome in the ignition and drying region.

See also Section VII-D.5.b.(1).

*(2) Disadvantages.* The more sophisticated mechanical equipment associated with the rotary kiln incinerator substantially increases the cost of the International unit relative to conventional rectangular continuous systems.

Associated with the more sophisticated design of this incinerator concept relative to conventional systems are higher maintenance costs. These incrementally higher costs would be associated with the rotary kiln section of the facility and would be directly concerned with the structural and mechanical equipment and the kiln lining.

The relatively high velocities of the flue gases in the rotary kiln along with the agitation and attrition caused by the kiln rotation increase particulate loadings to the air pollution control device relative to conventional grate systems. The turbulence of the flue gas stream tends to continually re-entrain suspended particulate. While such particulate can be controlled with existing APC systems, higher costs will be experienced for equivalent stack emission standards than for conventional systems.

### c. Problem Areas

See Section VII-D.5.c.

### d. Economics of Continuous Feed, Ignition Grate Plus Burnout Kiln Construction Incineration Systems

*(1) Capital Investment.* Several installations of this type exist throughout the United States, the first being completed in 1941. Three sizes of furnace units are commonly available: 175, 250, and 300 tons per day (TPD). In treating the available data for these furnace systems, costs were adjusted to reflect 1969 costs in Boston, Massachusetts, and specialized subsystems such as the waste heat boiler and metal reclamation systems were deleted to bring these data to the basis presented in Section VII.A.

All available data referred to furnace units with a capacity of 300 TPD which, consistent with the imposed "design basis," were found to cost approximately $6,700/TPD.

If it is assumed that incineration units in a multiple-unit facility all have the same rated capacities and that the cost of incremental units of equivalent capacity is approximately the same, the estimated cost for a 600-TPD incinerator facility comprised of two, 300-TPD units would, therefore, be:

$$\frac{\$6700}{\text{TPD}} \times \frac{300\ \text{TPD}}{\text{unit}} \times 2\ \text{units} \cong \$4{,}000{,}000$$

Investment costs for facilities comprised of units with capacities different than 300 TPD are estimated in Figure VII-25. The following equation was used to develop these estimates:

$$\text{Investment Costs (\$)} = (\text{\# of units}) \times \$2{,}000{,}000 \times \left[\frac{\text{new unit capacity (TPD/unit)}}{300}\right]^{0.6}$$

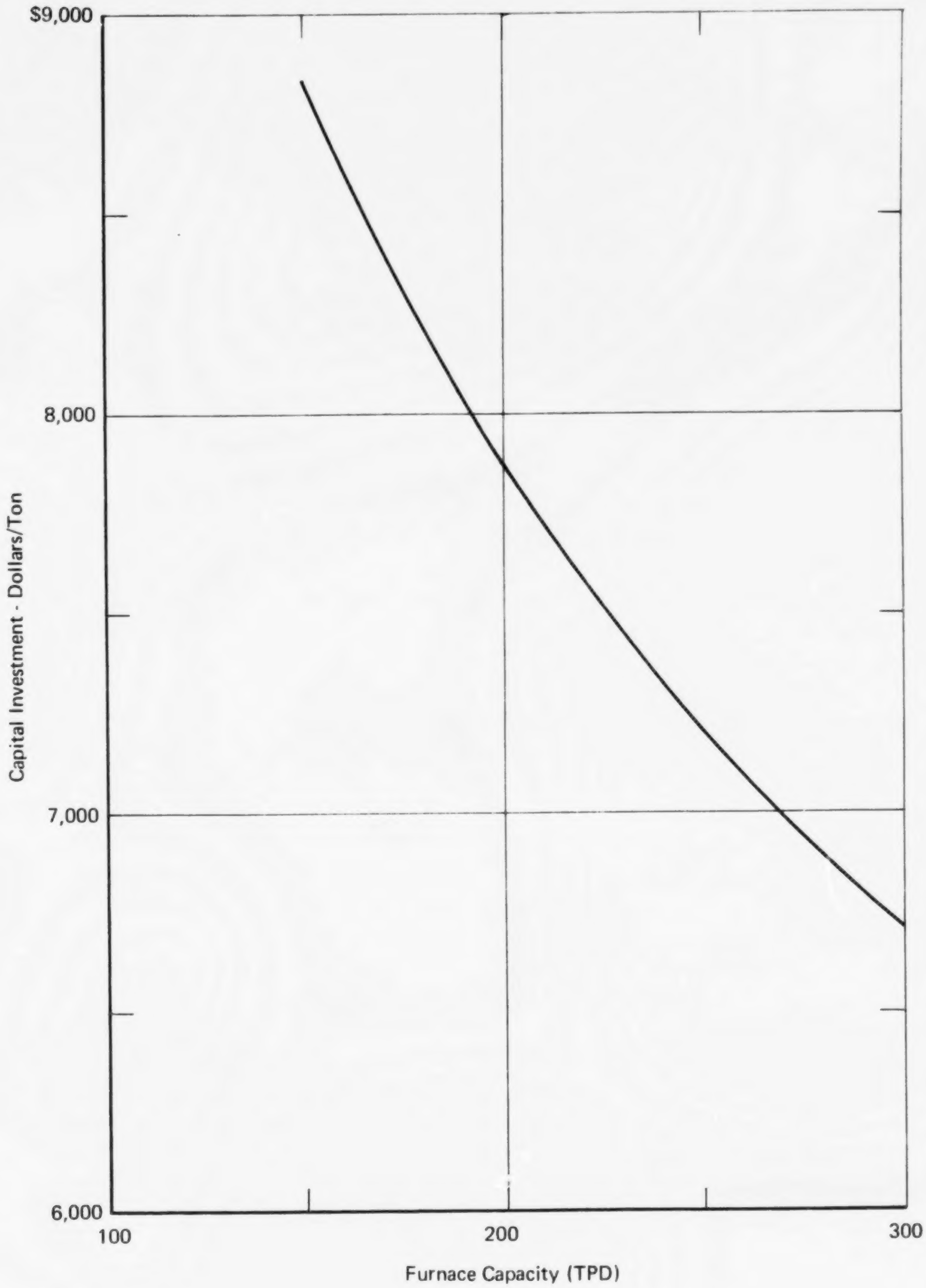


**FIGURE VII–25** ESTIMATED CAPITAL INVESTMENT FOR CONTINUOUS FEED-GRATE PLUS BURN-OUT KILN INCINERATION SYSTEMS

Although some savings may be made for multiple-furnace units from such items as less building space per installed TPD and more efficient construction labor and equipment utilization, these savings are small and their impact on investment costs and, more importantly, on the total operating cost, is probably negligible.

These costs are ADL estimates and do not reflect the policy or guarantees of International Incinerators, Inc.

*(2) Total Operating Costs.* Table VII-30 shows our estimates for "typical" total operating costs of a 600-TPD incineration system composed of two, 300-TPD units operating three shifts per day, 250 days per year.

The unit costs for power, water, operating labor and supervision were as presented in Section VII-A. Water was assumed to be recirculated except for those quantities utilized in the quenching of residue materials, the quantity evaporated in the cooling of flue gases down to 600°F, and miscellaneous quantities utilized during the operation of the incineration facility. The majority of the electricity utilized by this system is consumed in the operation of the I.D. fans.

Overhead and maintenance costs were developed as a percentage of labor plus supervision and capital investment, respectively. These percentages were based on engineering judgment and review of the limited public information on these costs.

Table VII-30 indicates that the variable costs (power and water) contribute approximately 12% to the total operating cost. Labor and maintenance contribute approximately 44%, with amortization and interest on the loan making up the remaining 44% of the operating cost for ignition grate and burnout rotary kiln.

Figure VII-26 illustrates the effects of rated capacity and the number of shifts employed on the operating costs of these incineration systems. The plant capacities in the horizontal axis up to 300 TPD were based on one incinerator unit. Capacities from 300 to 600 TPD were based on two incinerator units, each contributing 50% of the total capacity. Between 600 and 900 TPD, it was assumed that three units were utilized, each of equal capacity. Above 900 tons, it was assumed that four equal-sized units were utilized.

These costs are ADL estimates, however, and do not reflect the policy or guarantees of International Incinerators, Inc.

## TABLE VII-30

## ESTIMATED COST OF INCINERATION
## FOR CONTINUOUS FEED - IGNITION GRATE PLUS BURNOUT KILN CONSTRUCTION
(1969 dollars)

Reference Location: Boston, Massachusetts, mid-1969
Plant Capacity: 600 TPD (two, 300-TPD furnaces)
Load Factor: 250 days per year; 3 shifts per day
Annual Consumption: 150,000 tons refuse/year
Capital Investment: $4,000,000

| | Units | Dollars/Unit | Units/Ton Refuse Consumed | Dollars/Ton Refuse Consumed |
|---|---|---|---|---|
| **Variable Costs** | | | | |
| Electricity | kwh | $0.015 | 22.7 | 0.34 |
| Water | M Gal | $0.30 | 0.9 | 0.27 |
| | | | | $0.61 |
| **Semi-Variable Costs** | | | | |
| Labor | | | | |
| 1 crane operator per shift @ $5.00/hour | | | | 0.21 |
| 1 furnace operator per shift @ $5.00/hour | | | | 0.21 |
| 1 charging floor man per shift @ $3.00/hour | | | | 0.12 |
| 3 residue removal men per shift @ $3.00/hour | | | | 0.38 |
| 1 supervisor @ $14,000/year | | | | 0.09 |
| 1 weigh scale operator @ $5,500/year | | | | 0.04 |
| | | | | $1.05 |
| Overhead @ 40% of labor & supervision | | | | 0.42 |
| Maintenance and repair @ 2.5% of capital investment annually | | | | 0.67 |
| | | | | $2.14 |
| **Fixed Costs** | | | | |
| Amortization @ 5.0% of capital investment annually | | | | 1.33 |
| Interest on loan @ 3.0% of capital investment annually | | | | 0.80 |
| | | | | $2.13 |
| Total Costs | | | | $4.88 |

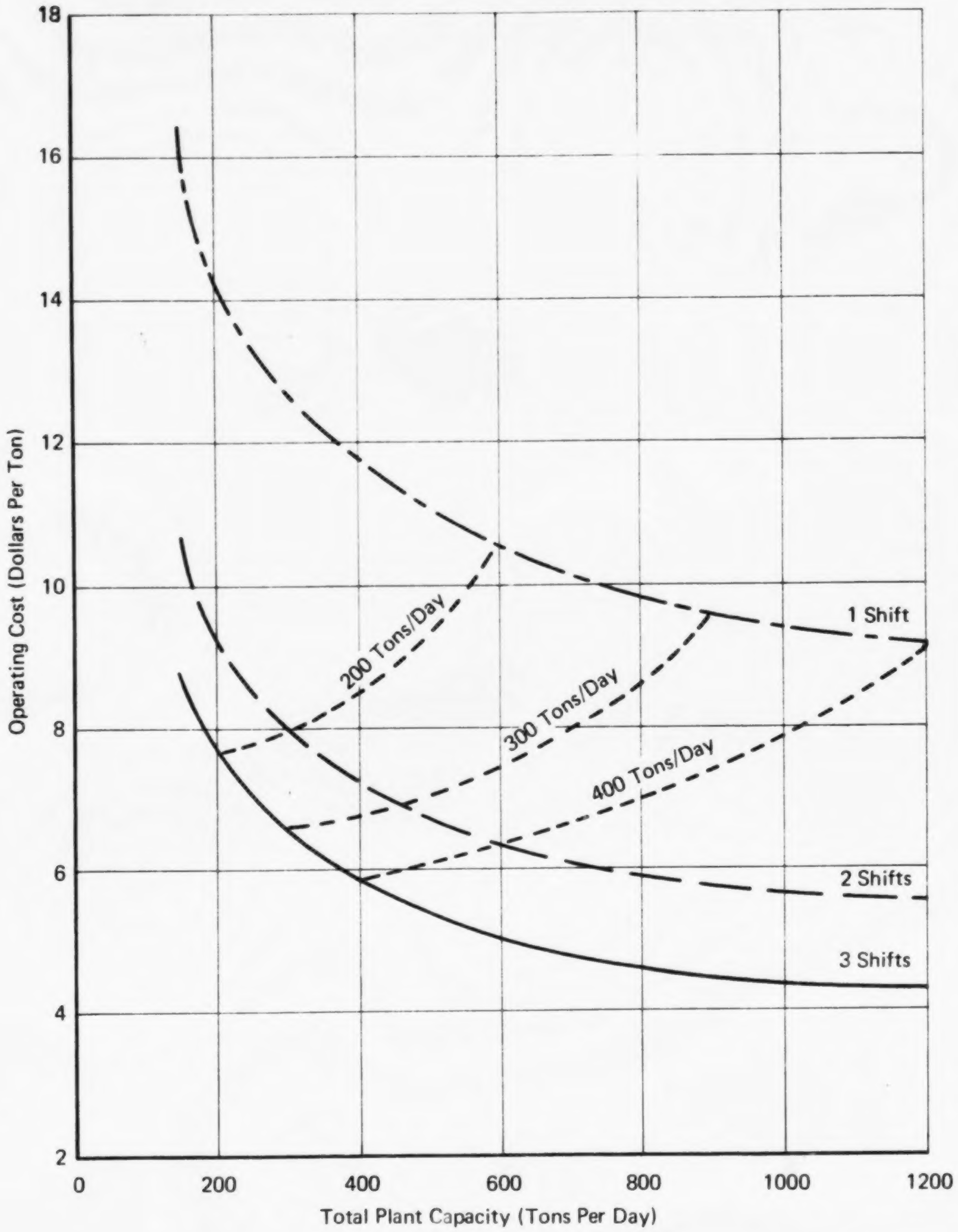


FIGURE VII–26 TOTAL OPERATING COSTS FOR CONTINUOUS FEED, IGNITION GRATE PLUS ROTARY KILN CONSTRUCTION INCINERATION SYSTEMS

Table VII-31 indicates the contribution of the various component costs comprising the total operating costs in Figure VII-26. These percentages were developed for four different rated plant capacities, for one-, two- and three-shift operation. These percentages allow for the modification of costs appearing in Figure VII-26 (as discussed in Section VII-A), to reflect assumptions other than those used to develop these component costs.

### TABLE VII-31

### DISTRIBUTION OF TOTAL OPERATING COSTS FOR CONTINUOUS FEED – IGNITION GRATE PLUS BURNOUT KILN

(%)

| **Plant Capacity** | 300 TPD | | | 600 TPD | | | 900 TPD | | | 1200 TPD | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Shifts/Day** | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| **Cost** | | | | | | | | | | | | |
| Power | 2 | 4 | 5 | 3 | 6 | 7 | 4 | 6 | 8 | 4 | 6 | 8 |
| Water | 2 | 3 | 4 | 3 | 4 | 6 | 3 | 5 | 6 | 3 | 5 | 6 |
| Labor and Overhead | 24 | 32 | 37 | 19 | 25 | 30 | 14 | 20 | 24 | 12 | 17 | 21 |
| Maintenance | 10 | 12 | 13 | 10 | 12 | 14 | 11 | 13 | 15 | 11 | 14 | 15 |
| Capital Charges | 62 | 49 | 41 | 65 | 53 | 43 | 68 | 56 | 47 | 70 | 58 | 50 |
| Total | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

### 8. Continuous Feed Systems: Volatilizing Kiln and Burnout Grate Construction

#### a. Process Description

Figure VII-27 schematically shows a rotary kiln incinerator system with associated burnout grate. The rotary kiln may be of varying lengths and diameters, depending upon the degree of burnout required and the capacity of the unit. One concept that has been proposed is a kiln 85 feet long with a diameter of 15 feet with an associated burnout grate 8 feet wide and approximately 33 feet long. A unit of this size is envisioned to have a capacity of approximately 400 tons per day of 4500-Btu-per-pound refuse.

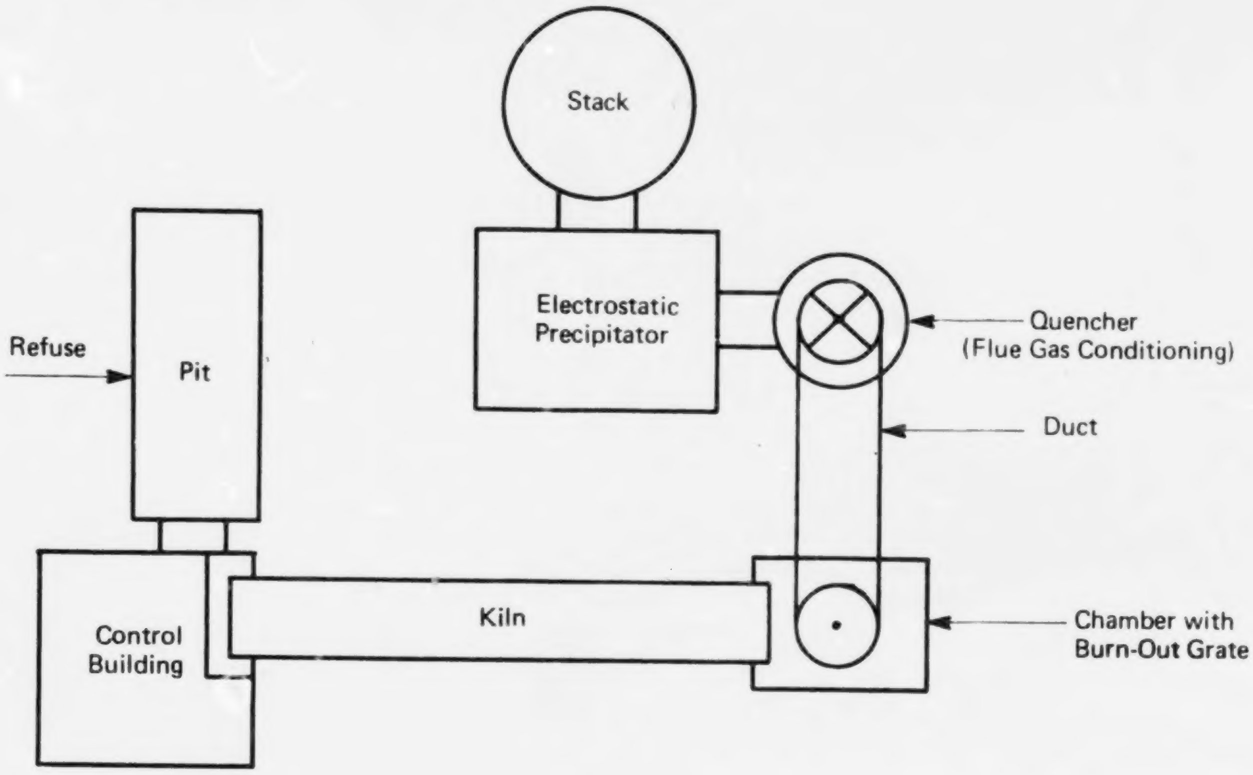

Stack
Electrostatic Precipitator
Quencher (Flue Gas Conditioning)
Duct
Refuse
Pit
Control Building
Kiln
Chamber with Burn-Out Grate

**FIGURE VII–27** SCHEMATIC DIAGRAM OF KILN PLUS BURN-OUT GRATE INCINERATOR SYSTEM

By utilizing this kiln-grate combination, the optimum advantages of both the rotary kiln and grate-type incineration techniques are exploited. Within the rotary kiln, refuse materials such as fats, plastics and metals with low melting points, which are frequently responsible for grate fouling or undergrate fires, will be burned out or reduced to an innocuous residue in the refractory-lined grateless kiln prior to reaching the grate section. Consequently, no problems in grate fouling or plugging would be expected. The burnout grate following the rotary kiln section permits the use of a shorter kiln. The problems of combustion control and refuse distribution associated with longer kilns are, therefore, substantially reduced.

Combustion control in the rotary kiln section is maintained by air supply and/or refuse wetting at the feed end of the kiln. By this means, combustion within the kiln section could be substoichiometric if so desired, to reduce temperatures and the likelihood of liquid slag formation and refractory damage. Combustion control on the grate section would be obtained as on the burnout grate in conventional incinerators. In addition, a substantial ash bed could be maintained on the grate to protect it from overheating. The residence times in the kiln and on the grate sections can be varied independently to accommodate the different physical and chemical characteristics of refuse materials.

The flue gases generated within the rotary kiln and above the grate section will first pass into a refractory-lined secondary chamber and then into a horizontal, refractory-lined cylindrical chamber envisioned to be approximately 50 feet long and 10 feet in diameter for a 400-TPD unit. The flue gases proceeed from the horizontal chamber through a dry-bottom water spray quenching unit. This quenching unit cools the flue gases to an appropriate temperature prior to its entrance into a suitable air pollution control device and thence to the stack. In this concept, an electrostatic precipitator will be utilized as the air pollution control system, with the gases being cooled to 600°F.

The residue material passes from the grates into ash receiving hoppers or to other suitable residue handling and removal systems. With such a system, it is speculated that residue quality will equal that for the system using grates and a kiln in the reverse order.

Air pollution from incinerators of this type is, at best, a speculation. If low gas velocities can be maintained in the kiln, particulate entrainment may be minimized. This, however, may be accomplished at the cost of increased production of combustible pollutants. As the grate sections will require less air flow than when volatilization is occurring, it is likely that ash emissions will be reduced. The net air pollution potential is thus uncertain.

b. Advantages and Disadvantages

*(1) Advantages.* The grateless kiln alleviates the problems of grate plugging or undergrate burning, as it is anticipated that troublesome refuse materials will be burned out in the kiln.

Because of the variability of the speed of the kiln and grates, it is possible to obtain relatively high residence times for complete burnout of even relatively large chunks of wood.

The rolling action of the refuse within the rotary kiln continually exposes unburned refuse surfaces, contributing to the efficient burnout of combustible matter.

The rotary kiln system should provide efficient volume reduction of the residue material.

See also Section VII-D.5.b.(1).

*(2) Disadvantages.* Although there seems to be a large degree of flexibility in combustion control, successful control of the combustion process may be somewhat difficult. There are a number of methods for control, such as combustion air modulation, use of water sprays, and the variation of residence time. The proper utilization of these control methods, however, depends upon the skill and experience of the operating and supervisory personnel.

The relatively high velocities of the flue gases in the rotary kiln along with the vigorous agitation and attrition caused by the kiln rotation may increase particulate entrainment and subsequent dust loads at the air pollution control device relative to those for conventional grate systems.

The more sophisticated mechanical equipment associated with the rotary kiln incinerator substantially increases its capital costs relative to conventional systems.

Associated with the more sophisticated design of this incineration concept are higher maintenance costs. These incrementally higher costs would be associated with the rotary kiln section of the facility and would be directly concerned with the structural and mechanical equipment and the kiln lining.

Direct contact of the burning refuse bed with the lining of the rotary kiln may cause fluxing of the refractory. However, if the combustion process (temperature) can be controlled along the length of the kiln, hot spots which lead to refractory degradation can be minimized.

### c. Problem Areas

This system represents an untried incineration concept; consequently, some degree of technical risk is involved. However, grates and refractory-lined kilns are presently utilized in the incineration industry, though in a different relationship, and kiln combustion systems are common in industrial practice. The degree of risk associated with this incineration concept, therefore, should not be an overriding consideration.

The successful operation of this incineration system requires skilled operator and supervisory personnel. Therefore, the incinerator personnel must be carefully selected and trained.

Combustion control and air pollution minimization are important, but the solutions to these problems are still unknown. Engineering evaluation and demonstration is clearly necessary.

See also Section VII.D.5.c.

### d. Economics of Continuous Feed, Volatilizing Kiln and Burnout Grate Incineration System

*(1) Capital Investment.* An analysis of this system indicates that for a facility consisting of:

- one, 400-TPD unit with associated process equipment,
- building,
- refuse pit,
- foundations and land preparation,
- piping, instrumentation, and controls, and
- electrostatic precipitator air pollution control device

will cost an estimated $2,700,000 (in Boston, Mass., 1969). This includes $1,200,000 for the building, foundations, pit, and land improvements. The building is envisioned to be of brick construction and enclose the secondary chamber, pit, tipping floor, residue handling system, offices, and lockers and associated facilities.

Although the investment costs of one-stage kiln units of different capacities have not been evaluated, we visualize that costs for such facilities can be estimated by applying the six-tenths scale factor as follows:

$$\text{Cost of facility} = (\text{number of furnaces}) \times \$2{,}700{,}000 \times \left[\frac{\text{capacity of furnaces comprising facility (TPD/unit)}^{0.6}}{400}\right]$$

*(2) Total Operating Costs.* Table VII-32 shows estimates for "typical" operating costs for a 400-TPD incineration facility. The facility has one, 400-TPD unit and operates three shifts per day, 250 days per year.

Unit costs for power, water, operating labor, and supervision were as presented in Section VII-A. Overhead and maintenance costs were developed as a percentage of labor plus supervision and capital investment, respectively. These percentages were based on engineering judgment and review of the limited public information on similar systems.

Table VII-32 shows that the variable costs (power and water) contribute approximately 11% of the total operating cost. Labor and maintenance contribute approximately 49% with amortization and interest on the loan making up the remaining 40% of the operating costs for this rotary kiln system.

The percent contributions of variable, semi-variable and fixed costs to the total operating costs as described above are similar to those for rectangular continuous incineration systems. This similarity indicates that the operating costs as a function of capacity and number of shifts will vary similar to the operating cost curves developed for the rectangular continuous incineration system (Figure VII-22).

## 9. Continuous Feed Systems: Three-Stage, Rotary-Kiln Construction

### a. Process Description

Figure VII-28 is a schematic diagram of a multiple rotary-kiln incinerator system. The kiln consists of concentric refractory-lined rotating cylindrical sections. The sections become progressively greater in diameter in the down stream direction, and in one embodiment, would be rigidly welded together and rotated by a single drive. A three-stage kiln of this type, rated at a capacity of 400 TPD is envisioned to be approximately 150 feet long with increasing diameters of 11 feet, > 13 feet, and > 15 feet, respectively.

The multiple-kiln concept has not been used in incineration practice although mechanically similar systems of kiln have been used in the pyroprocessing industry. This concept is suggested by ADL as a possible solution to several problems common to conventional grate-type, kiln-type and grate-kiln incinerators. Kilns have an inherent advantage over grate systems when refuse containing fusible plastics and combustible or putrescible liquids must be burned. With grates, these liquids may pass through the grate openings and subsequently burn underneath, causing grate damage and incinerator outages. Kilns are also not subject to fouling from wires, melted bottles, slag, etc. Difficulties with kiln incinerators in the past, however, have resulted from the single-shell design, where

## TABLE VII-32

## ESTIMATED COST OF INCINERATION FOR A CONTINUOUS FEED, VOLATILIZING AND BURNOUT GRATE INCINERATION SYSTEM

(1969 dollars)

Reference Location: Boston, Massachusetts, mid-1969
Plant Capacity: 400 TPD (one, 400-TPD furnace)
Load Factor: 250 days per year; 3 shifts per day
Annual Consumption: 100,000 tons refuse/year
Capital Investment: $2,700,000

| | Units | Dollars/Unit | Units/Ton Refuse Consumed | Dollars/Ton Refuse Consumed |
|---|---|---|---|---|
| **Variable Costs** | | | | |
| Electricity | kwh | $0.015 | 22.7 | 0.34 |
| Water | M Gal | $0.30 | 0.9 | 0.27 |
| | | | | $0.61 |
| **Semi-Variable Costs** | | | | |
| Labor | | | | |
| 1 crane operator per shift @ $5.00/hour | | | | 0.31 |
| 1 furnace operator per shift @ $5.00/hour | | | | 0.31 |
| 1 charging floor man per shift @ $3.00/hour | | | | 0.19 |
| 2 residue men per shift @ $3.00/hour | | | | 0.38 |
| 1 supervisor @ $14,000/year | | | | 0.14 |
| 1 weigh scale operator @ $5,500/year | | | | 0.06 |
| | | | | $1.39 |
| Overhead @ 40% of labor & supervision | | | | 0.56 |
| Maintenance and repair @ 2.5% of capital investment annually | | | | 0.68 |
| | | | | $2.63 |
| **Fixed Costs** | | | | |
| Amortization @ 5.0% of capital investment annually | | | | 1.35 |
| Interest on loan @ 3.0% of capital investment annually | | | | 0.81 |
| | | | | $2.16 |
| Total Costs | | | | $5.40 |

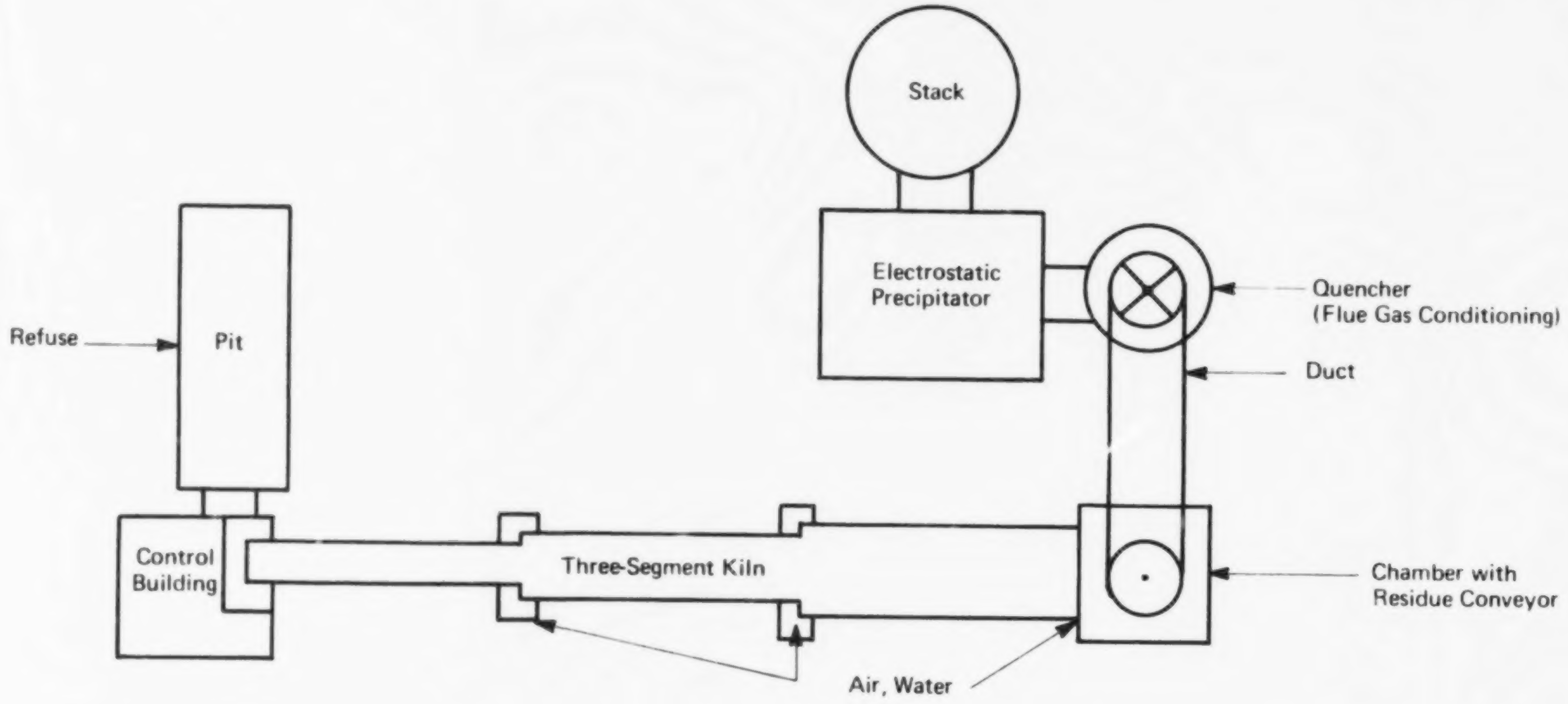

Stack
Electrostatic Precipitator
Quencher (Flue Gas Conditioning)
Duct
Refuse
Pit
Control Building
Three-Segment Kiln
Chamber with Residue Conveyor
Air, Water

FIGURE VII–28 SCHEMATIC OF THREE-SEGMENT ROTARY KILN INCINERATION SYSTEM

all of the combustion air is blown into the system at one end. This condition leads to high particulate carry-over. Also, the rapid ignition of a large fraction of the refuse over a short length of kiln (as with dry refuse) and the abundant availability of combustion air may lead to very high localized heat release rates with consequent overheating of the kiln walls and shell. Similarly, the abundance of air may quench the combustion for difficult-to-burn refuse.

The multiple-kiln concept in incineration design permits more flexibility in the control of the combustion process than for single-stage kilns. Secondary air or cooling water sprays may be introduced at the "breaks" along the kiln to control the rate and degree of combustion reactions and consequent heat release along the kiln length. This feature may help in minimizing hot spots, a problem in one-stage kiln systems. Also, delayed air addition avoids high gas velocities at the feed end. Low velocities are also provided by the increasing flow area along the kiln.

The rotary kiln provides regular and continuous agitation without the utilization of grates. In this kiln design, additional agitation is obtained as the refuse spills over from one stage of the kiln to the next.

The speed of the kiln may be varied to control refuse residence time as appropriate for refuse of different physical and chemical characteristics. A modification to this design could include independent drive systems for each kiln section so that the rpm of each stage could be individually controlled. This adds another degree of flexibility in controlling the combustion process in each kiln segment. The economic discussions to follow, however, consider only the three-stage kiln rigidly welded together and rotated with a common drive together with other combustion chambers and equipment as shown in Figure VII-28.

Both the residue materials and flue gases from the rotating kiln discharge into a refractory-lined secondary chamber. At the bottom of the secondary chamber, a short conveyor grate could be installed to receive the residue.

The flue gases pass through the secondary combustion chamber and then enter a horizontal refractory-lined cylindrical chamber, envisioned to be 10 feet in diameter and approximately 50 feet long for a 400-TPD unit. The flue gases proceed from this horizontal chamber, are cooled in a dry-bottom water spray quenching unit, pass through the air pollution control device, and thence to the stack. In this concept, an electrostatic precipitator is recommended as the air pollution control system.

Residue quality from such a device should be superior to that of conventional systems as has been demonstrated in existing kiln systems. Siftings, a common contributor to unburned combustible in the residue, are eliminated, further improving residue quality.

The air pollution potential of this rotary kiln system is uncertain. It is likely that heavy fly ash entrainment will occur as a consequence of the abrasion, attrition and entrainment of residue in the kiln. While some gravity settlement in the secondary chamber will occur, it is likely that dust loadings higher than found in contemporary continuous feed systems will be experienced. These emissions, however, could be readily controlled with existing APC devices. Combustible particulate and gaseous pollutant levels are uncertain, but the long kiln and air control leads to speculation that they would appear in lower concentrations than in contemporary plants.

b. Advantages and Disadvantages

*(1) Advantages.* This rotary kiln system operates without the utilization of grates and, therefore, the corrosion, plugging, and undergrate burning problems common to grate systems are alleviated.

Complete burnout of most refuse is facilitated by both the long residence time and agitation within the kiln.

A greater degree of combustion control is provided with this incineration concept than in earlier single-stage kiln systems. The combustion rates can be controlled along the length of the kiln by controlling the amounts of secondary air or cooling water sprays introduced along the kiln.

A distinct advantage associated with the rotary kiln concept is the efficiency volume reduction of the residue material as described previously.

See also advantages 1.5. from continuous-feed, rectangular construction, above.

*(2) Disadvantages.* See Disadvantages 1, 3, 4, and 5 from continuous feed systems–volatilizing kiln and burnout grate construction.

Accompanying the high linear gas velocities through the kiln and the high degree of agitation and attrition of residue ash by the rotation of the kiln, an increase in the particulate loading to the air pollution control device is anticipated. Offsetting these effects, however, are both the increasing kiln diameter in the direction of the gas flow which incrementally decreases the linear velocity of the gas through the system and the settling which takes place in the large secondary chamber.

### c. Problem Areas

See problem areas 1-3 for continuous-feed systems, volatilizing kiln, and burnout grate construction.

Despite the intended flexibility in combustion control, long kiln combustors may present problems in obtaining an acceptable distribution of heat release to prevent "hot-spots" with consequent refractory damage. Tests of this concept are required, therefore, to evaluate the importance of this problem.

### d. Economics of Continuous-Feed, Three-Stage, Rotary-Kiln Incineration System

*(1) Capital Investments.* An analysis of cost data for industrial kilns suggests that a three-stage, rotary-kiln incinerator system consisting of:

- one 400-ton per day unit with associated process equipment,
- the associated building and structural supports,
- the refuse pit,
- foundations and land preparation,
- piping, instrumentation and controls,
- electrostatic precipitation, I.C. fans, and associated ducting

will cost an estimated \$2.9 million (in Boston, Massachusetts, 1969). This includes \$1.2 million for the building, foundation, pit and land improvements. Although the cost of three-stage kiln units of different capacities have not been evaluated, we visualize that costs for such facilities can be estimated by applying the six-tenths scale factor as follows:

$$\text{Cost of facility} = (\text{the number of furnaces}) \times \$2{,}900{,}000 \times \left[\frac{\text{capacity of furnaces} \quad (\text{TPD/unit})^{0.6}}{400}\right]$$

Table VII-33 shows the typical operating costs for a 400-ton per day incineration facility. The facility has one 400-ton per day unit and operates three shifts per day, 250 days per year.

Unit costs for power, water, operating labor, and supervision were as presented in the Introduction to Chapter VII. Overhead and maintenance costs were developed as a percentage of labor plus supervision and capital investment, respectively. These percentages were based on engineering judgment and analysis of costs for industrial kiln systems.

## TABLE VII-33

## ESTIMATED COST OF INCINERATION USING A CONTINUOUS-FEED, THREE-STAGE, ROTARY-KILN INCINERATION SYSTEM

### (1969 dollars)

| | |
|---|---|
| Reference Location: | Boston, Massachusetts, 1969 dollars |
| Plant Capacity: | 400 TPD (one, 400-TPD furnace) |
| Load Factor: | 250 days per year; 3 shifts per day |
| Annual Consumption: | 100,000 tons refuse/year |
| Capital Investment: | $2,900,000 |

| | Units | Dollars/Unit | Units/Ton Refuse Consumed | Dollars/Ton Refuse Consumed |
|---|---|---|---|---|
| **Variable Costs** | | | | |
| Electricity | kwh | $0.015 | 22.7 | 0.34 |
| Water | M Gal | $0.30 | 0.9 | 0.27 |
| | | | | $0.61 |
| **Semi-Variable Costs** | | | | |
| Labor | | | | |
| 1 crane operator per shift @ $5.00/hour | | | | 0.31 |
| 1 furnace operator per shift @ $5.00/hour | | | | 0.31 |
| 1 charging floor man per shift @ $3.00/hour | | | | 0.19 |
| 2 residue men per shift @ $3.00/hour | | | | 0.38 |
| 1 supervisor @ $14,000/year | | | | 0.14 |
| 1 weigh scale operator @ $5,500/year | | | | 0.06 |
| | | | | $1.39 |
| Overhead @ 40% of labor & supervision | | | | 0.56 |
| Maintenance and repair @ 2.5% of capital investment annually | | | | 0.72 |
| | | | | $2.67 |
| **Fixed Costs** | | | | |
| Amortization @ 5.1% of capital investment annually | | | | 1.45 |
| Interest on loan @ 3.0% of capital investment annually | | | | 0.87 |
| | | | | $2.32 |
| Total Costs | | | | $5.60 |

Table VII-33 shows that the variable costs (power and water) contribute approximately 11% of the total operating costs. Labor and maintenance contribute approximately 48% with amortization and interest on the loan making up the remaining 41% of the operating costs for the three-stage rotary kiln system.

The percent contribution of variable, semivariable, and fixed costs to the total operating costs as described above are similar to those for rectangular continuous incineration systems. This similarity indicates that the operating costs as a function of capacity and number of shifts would vary similar to the operating cost curves developed for the rectangular continuous system shown in Figure VII-22 of Chapter VII.

### 10. Continuous-Feed Systems: Waterwall Construction (Grate Burning)

#### a. Process Description (see also Section IV.B.)

The continuous-feed incinerator with waterwall construction and grate burning is similar in many respects to existing plants with refractory wall construction. Refuse feeding, grate, siftings removal and ash handling subsystems are or can be identical. The primary differences lie in the operating characteristics of the units. For example, since the boundaries of the waterwall system can absorb high heating loads without damage, it becomes practical to operate at low excess air levels (50-100%) in contrast to most refractory systems which operate above 150% excess. Also, most waterwalls are fabricated without seams, reducing the leakage of air into the chamber to that associated with peep-holes, stoking doors and the like.

Waterwall incineration systems have been used extensively in Europe. The development of these systems was spurred by joint ventures between municipalities and power companies and by the high (relative to the U.S.) costs of fossil fuels for steam-raising applications. The availability of steam markets in the form of power plants and municipal steam distribution networks also contributed to their popularity. As a result, sophisticated plants with capacities greater than 2000 TPD have been built. In general, these plants are under the direction of a graduate mechanical engineer, almost a necessity for the more sophisticated plants. In the United States, there are only a few operating waterwall incinerators, most of which are in use in industry. Several municipal plants, however, are either in the planning stages or actually under construction.

In waterwall incineration systems, refuse is fed from the pit to the charging hopper and down through a water-cooled charging chute. It is especially desirable that the crane operator mix the refuse to provide a more consistent refuse heating value and consequent steaming rate. The refuse moves by gravity down the feed chute and onto the drying and ignition stoker, generally of three types – traveling, rocking, or reciprocating. European installations have used all three, plus the barrel grate developed in Düsseldorf. Because water-cooled boiler tubes have replaced air-cooled or insulated refractory walls within the combustion chamber, the temperature limitations imposed on conventional refractory furnaces are relaxed. The quantities of underfire and overfire air can thus be adjusted to maintain optimum combustion conditions. Air or steam jets can be used to obtain turbulence in the overfire volume without overcooling the combustion space.

About a third of the heat released by the burning refuse is absorbed by the waterwalls as radiation from the refuse bed and gases and, to a lesser extent, from convection. The water-cooled furnace operation is usually *followed* by banks of convection boiler tubes after going through which the gases may be further cooled by an economizer. The extent of the economizer surface, which is justifiable, and the installation of an air preheater depend upon the economics of the particular system.

In several plants, superheater tubes are used. Due to accelerated corrosion on these tubes, however, protection with castable refractory is necessary. Soot blowers or their equivalent are necessary for all tube surfaces.

The steam generated by the unit may be sold or used for space heating, operating auxiliaries, or generating electricity. When the steam demand is low, or as an alternative to the uses above, the heat may be dissipated by an air-cooled condenser. The economic analysis to follow does not include by-product steam credits because of the variations in steam utilization as well as the variations in boiler efficiency and the price of steam. The economics of heat recovery in the United States are discussed in detail in Appendix F.

This system can utilize standard air pollution control devices, but is particularly well suited to dry collectors (cyclones, precipitators, bag filters). In the economic analysis to follow, it was assumed that an electrostatic precipitator was utilized as the air pollution control device. It should be noted that as a result of dry flue gas cooling and the lower excess air levels in waterwall systems, the electrostatic precipitator is smaller (lower cost) than for refractory systems (see Appendix B).

The residue quality for waterwall systems should be similar to that for the refractory wall counterparts. Possibly, improved combustion control and more comprehensive operator training may result in some improvement. Many of the problems (very wet refuse) which lead to reduced residue quality, however, are not solved by waterwall construction.

The mineral particulate emission from waterwall furnaces is anticipated to be the same as for the refractory wall counterparts. Combustible pollutants should be emitted in somewhat smaller quantities as a consequence of the improved opportunities for combustion control.

b. Advantages and Disadvantages

*(1) Advantages.* A significant advantage of this system is that there are no refractory walls to limit the combustion temperatures in the primary combustion chamber. Therefore, combustion control, rather than temperature control, can assume pre-eminence in establishing operating parameters. In particular, less overfire air may be necessary to limit temperatures in the primary chamber. If proportionally more underfire air is utilized, the grate burning rate can be increased; however, an increase in mineral particulate loadings then occurs. The result of maintaining higher flame temperatures within the primary chamber may result in more efficient burnout of refuse (better residue quality) and less combustible pollutants leaving the primary chamber if the mixing processes in the overfire volume are adequate.

The reliability of modern stoker-fired boiler units is such that continuous operation from one annual shutdown to the next is commonplace. In fossil fuel-burning installations, waterwalls have eliminated the periodic shutdown for furnace cleaning and furnace maintenance. While refuse materials cause greater difficulties than solid fossil fuels, excellent reliability has been observed in European plants. High Btu material will not require radical changes in operating procedures as is necessary when burned in refractory furnaces.

Electrostatic precipitators (or other air pollution control equipment) are safe from overheating, since any increase in the combustion rate or Btu content of the refuse will only reflect an increase in steam output without any appreciable change in the exit temperatures from the boiler or economizer.

Boiler units have earned enviable safety records. The fact that the incinerator plant is a steam-generating facility rather than just an incinerator also tends to buoy the morale of the operator, resulting in better plant operation.

Because the flue gases are cooled within the boiler system and not with the use of water sprays, the plume is significantly dryer, thereby alleviating corrosion and aesthetic problems commonly associated with a wet plume.

See also advantages 1.5 from continuous-feed, rectangular construction.

*(2) Disadvantages.* The waterwall furnace incinerator has a high initial cost and a higher operating labor cost than refractory wall counterparts. The increase

in labor cost reflects the necessity of extra labor requirements for operating and control of the boiler system as well as more highly trained and experienced regular operating personnel. However, the application of industrial boiler room practices may develop procedures and controls which will enable the use of the same ratio of personnel to incinerator tonnage as with refractory incinerators.

More mixing of the refuse is desirable than with refractory incinerators. In contrast to refractory-type furnaces, where the large amount of hot brick-work tends to have a fly-wheel effect on ignition, water-cooled furnaces depend greatly on the feedback of heat from the burning bed. A surge of wet material, therefore, can have a disadvantageous effect on burning characteristics.

Because of the high capital investment and the long start-up time, this incineration concept is more amenable to a three-shift operation than to one- or two-shift operation.

The investment cost associated with waterwall boiler systems is often justified by an assumed by-product credit from the sale of steam. In supplying steam, the customer generally requires a high degree of reliability with assurance that constant steam will be supplied at all times. This reliability criterion may result in incremental costs because it is predicated either on duplication of equipment or a contractual arrangement with another supplier of steam. Either alternative, of course, results in extra cost to the incineration facility. On the other hand, combined-firing systems may be attractive, particularly when the fossil fuel provides most of the heat input. In this situation, stable, reliable steam flows may be assured. The combined-firing concept is now being studied under NAPCA sponsorship.

See disadvantages 2. and 3. for continuous-feed, rectangular construction.

### c. Identification of Problem Areas

The presence of metal boiler tubes in contact with incinerator flue gas streams poses the problem of corrosion and erosion. European plants have experienced problems, especially near the grate line and in the high-temperature superheater tubes. The high incidence of alkali metals and hydrogen chloride in incinerator flue gas and particulate suggests caution in selection of operating temperatures and construction materials.

The waterwall boiler concept is relatively new in the United States, with only a few installations presently on-stream or near completion. This concept, therefore, has associated with it risks and unknown problem areas which are possible with a new and relatively untested incineration concept.

The many advantages of waterwall construction may be lost if means are not found to use the steam generated. Applications within the context of the municipal establishment should be sought especially (e.g., sewage sludge treatment, desalination, heating municipal buildings, power generation).

See problem areas 1-4 from continuous-feed, rectangular construction.

### d. Economics of Continuous-Feed, Waterwall-Construction, Grate-Burning Incineration Systems

*(1) Capital Investment.* Figure VII-29 shows the estimated investment costs for waterwall construction incinerator plants with convection boilers and electrostatic precipitators. This figure has been compiled from bid prices, published estimates, and our own estimates. The values include 10% for site preparation. Also included are costs for steel stack and the building with housed pit, but no housing over the tipping floor. As steam demand may not exist during periods of time when the incinerator is operating, the cost for an air condenser has also been included. As indicated in Figure VII-29, the investment curve is expressed as a function of tons per day per furnace for plants with two furnaces. These costs would not change appreciably for single- or other multiple-furnace plants.

The two extreme lines on this curve indicate the probable cost ranges, which, of course, would be predicated on the details in design and specifications. The ranges, as indicated, are not in any way to be construed as a variation in cost due to geographical location as all capital costs were based on mid-1969 dollars for Boston, Massachusetts.

*(2) Total Operating Costs.* Table VII-34 was developed to illustrate the typical operating costs for a 1200-TPD waterwall boiler incineration facility comprised of two 600-TPD systems. The facility will operate three shifts a day for 250 days a year. The assumptions inherent in the capital investment figure of $9,700,000 are those discussed previously. No steam credits were assumed (see Appendix F).

Table VII-35 indicates the percent contribution of the various component costs comprising the total operating costs from Figure VII-30. These percentages, developed for three different rated plant capacities, allow for the modification of costs appearing in Figure VII-30 as discussed in the Introduction to Chapter VII. They reflect assumptions other than those used to develop these component costs.

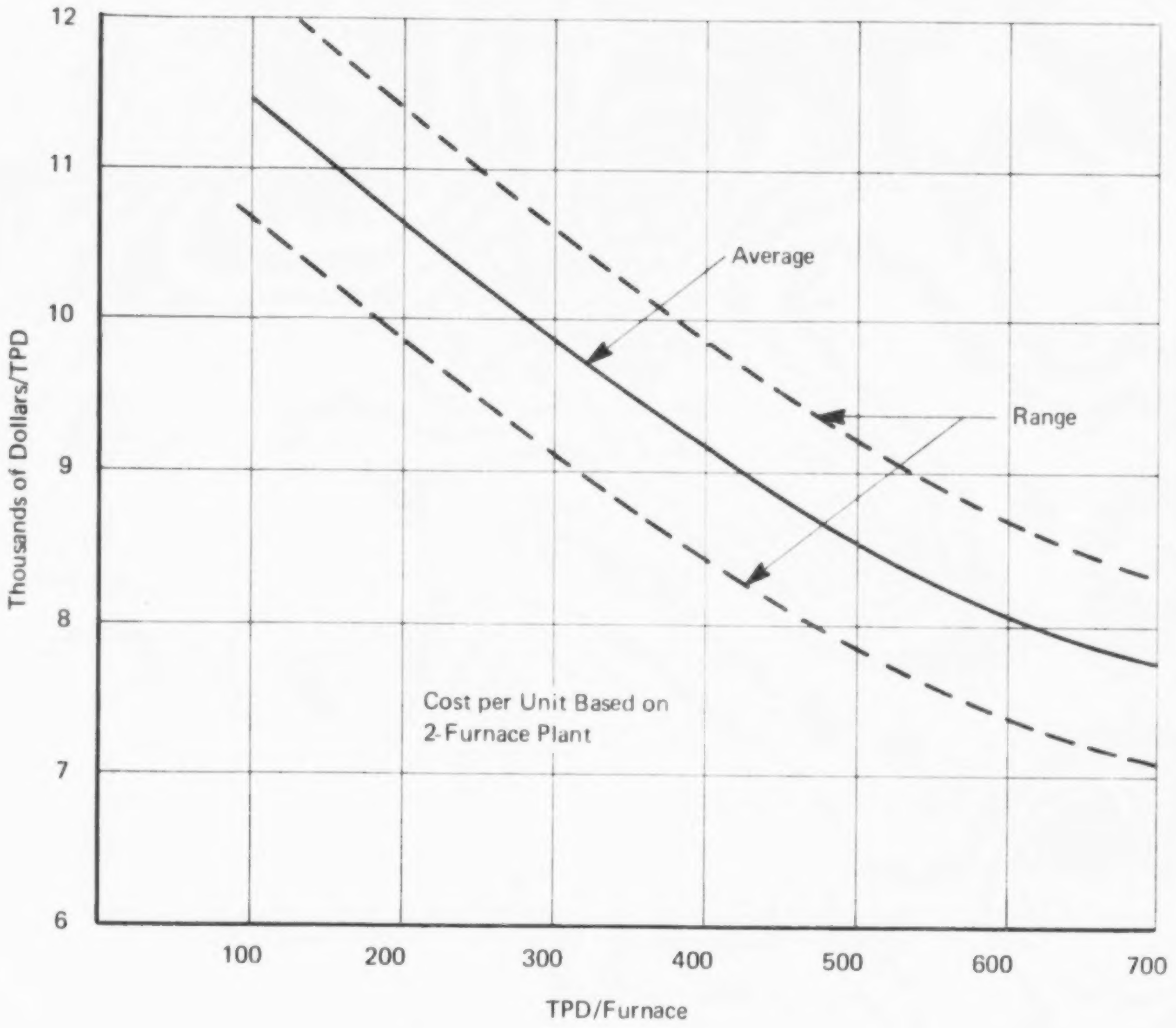


FIGURE VII–29 ESTIMATED 1969 COST OF INCINERATOR PLANT WITH BOILERS AND PRECIPITATORS

## TABLE VII-34

## ESTIMATED COST OF INCINERATION USING A CONTINUOUS-FEED, WATERWALL-CONSTRUCTION (GRATE-BURNING) INCINERATION SYSTEM

Reference Location: Boston, Massachusetts, 1969 dollars
Plant Capacity: 1200 TPD (two 600-TPD furnaces)
Load Factor: 250 days/year; 3 shifts/day
Annual Consumption: 300,000 tons refuse/year
Capital Investment: $9,700,000

| | Units | Dollars/Unit | Units/Ton Refuse Consumed | Dollars/Ton Refuse Consumed |
|---|---|---|---|---|
| **Variable Costs** | | | | |
| Electricity | kwh | $0.015 | 22.0 | 0.33 |
| Water | M gal. | $0.30 | 0.5 | 0.15 |
| | | | | $0.48 |
| **Semi-Variable Costs** | | | | |
| Labor | | | | 0.52 |
| 5 men per shift @ $5.00/hour | | | | 0.52 |
| 5 men per shift @ $3.00/hour | | | | 0.31 |
| 1 supervisor @ $14,000/year | | | | 0.05 |
| 1 weight scale operator @ $5,500/year | | | | 0.02 |
| | | | | $0.90 |
| Overhead @ 40% of labor & supervision | | | | 0.36 |
| Maintenance and repair @ 1.75% of capital investment annually | | | | 0.57 |
| | | | | $1.83 |
| **Fixed Costs** | | | | |
| Amortization @ 5.2% of capital investment annually | | | | 1.68 |
| Interest on loan @ 3.0% of capital investment annually | | | | 0.97 |
| | | | | 2.65 |
| Total Costs | | | | $4.96 |

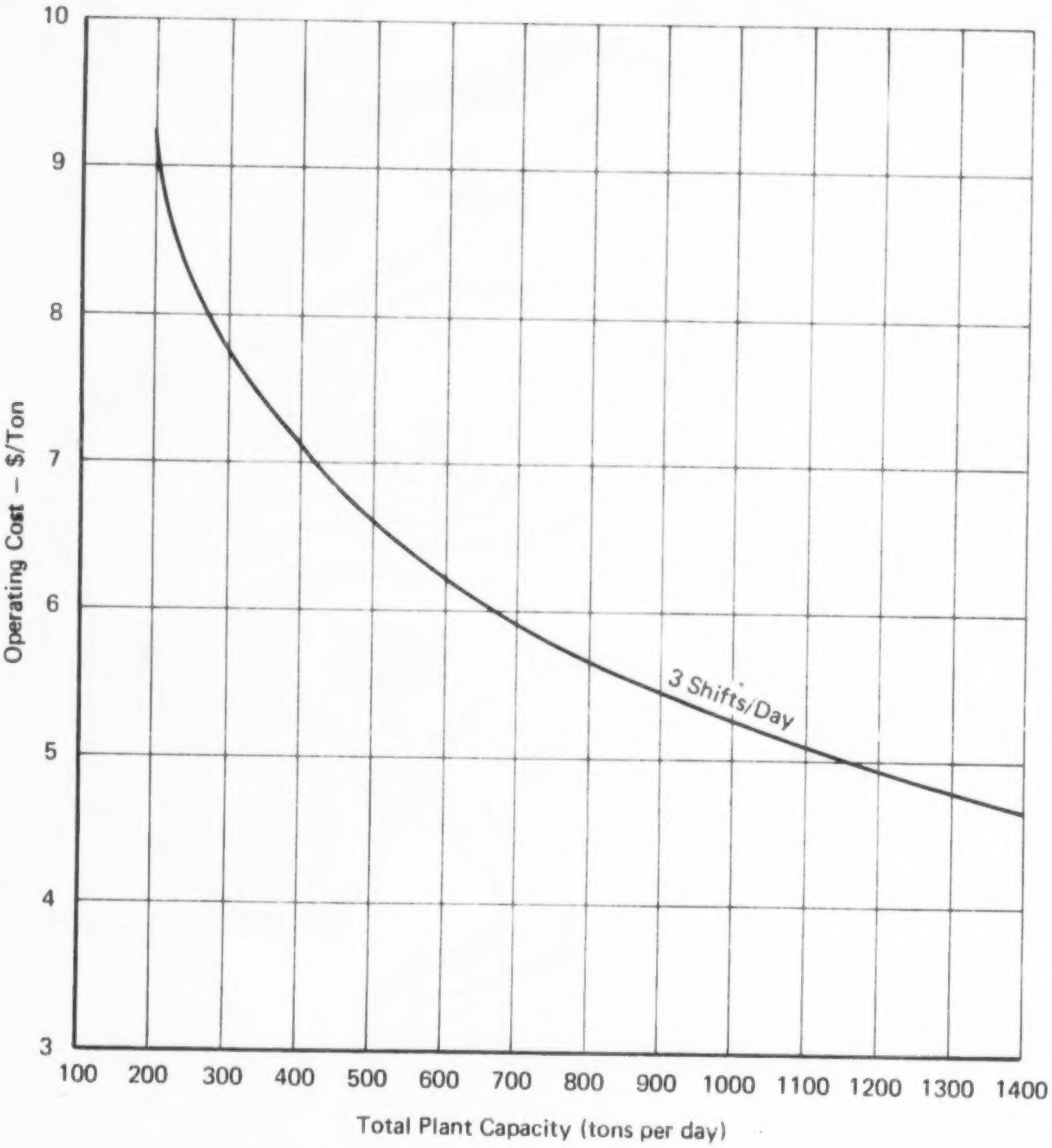


**FIGURE VII–30** TOTAL OPERATING COSTS – CONTINUOUS-FEED, WATER WALL-CONSTRUCTION INCINERATOR SYSTEMS (Grate Burning, No Steam Credits)

## TABLE VII-35

## DISTRIBUTION OF TOTAL OPERATING COSTS FOR CONTINUOUS-FEED, WATERWALL-CONSTRUCTION (GRATE-BURNING) SYSTEMS

(%)

| Plant Capacity | 200-TPD | 600-TPD | 1000-TPD |
|---|---|---|---|
| Shifts/Day | 3 | 3 | 3 |
| **Cost** | | | |
| Power | 4 | 6 | 6 |
| Water | 2 | 3 | 3 |
| Labor and Overhead | 44 | 26 | 27 |
| Maintenance | 9 | 12 | 11 |
| Capital Charges | 41 | 53 | 53 |
| Total | 100 | 100 | 100 |

### 11. Continuous-Feed Systems: Waterwall Construction (Suspension Burning)

#### a. Process Description

Pneumatic distribution of fuel into the firing chamber – or suspension burning – is a technique commonly utilized to burn baggasse, wood bark, corn stalks, lignite, and pulverized coal. For refuse incineration applications, it is envisioned that the refuse would be shredded and spread across a grate surface by pneumatic distributors. To reduce shredding costs and to facilitate uniform pneumatic transport, some separation of metal, glass, and stones may be required. The milled or shredded refuse (probably about 2″ top-size) would be transported to the furnace by conveyor and transferred to pneumatic distributors which would spread the refuse above the grate surface. Mechanical spreaders may be usable, but the low-bulk density of shredded refuse suggests that it is unlikely.

This type of feeding system, which offers the unique advantage of rapid drying and volatilization of the refuse in suspension, results in a faster, more efficient combustion relative to the conventional hopper and feed chute design. The grates may be of the automatic ash dumping, automatic ash lancing, or continuous-flow types. Larger plants require the continuous-flow grate design.

Other than the unique features related to the feeding and grate systems, this suspension burning concept is very similar to the waterwall boiler incineration system with conventional grate burning.

An alternative, closely related to the spreader-stoker concept described above, is based on use of a higher boiler with refuse injection taking place near the top of the radiant section. Here, a larger fraction of the burning would take place in suspension. Most likely, however, a greater degree of refuse subdivision (higher shredding costs) and increased capital investment (more waterwall area, steel-work and foundations) will be required with little improvement in performance. The remainder of this description and discussion of concept economics, therefore, is based on the spreader-stoker concept.

Spreader-stoker boilers could absorb between one-third and one-half of the heat released by the burning refuse in the waterwall area. The water-cooled suspension firing furnace would be followed by a bank of convective boiler tubes after which the gas could be further cooled by an economizer and air heater. The extent of the economizer and air heater surface which is justifiable depends upon the economics of the particular system being designed. The remarks on waterwall systems with grate burning relative to heat use and air pollution control systems apply here also.

Residue quality for suspension-burning systems should be excellent in comparison to that from other existing incinerators. Burnout of even high moisture refuse will be assisted by (a) the shredding process, (b) the high radiative heat transfer to the individual particles as they pass through the overfire flame envelope, and (c) the design characteristic which drops new feed on the top of an already burning refuse bed.

Air pollution control for suspension burning systems will require systems with much greater collection efficiency for equivalent stack emissions than existing units. Carry-over of particulate may be sufficient such that, as in coal-burning, spreader, stoker experience, soot blowers will not be necessary, the dust-laden ash providing sufficient tube scrubbing. However, dust re-injection may be required to obtain optimal burnout of carbon in the ash which settles in the bottom of the convection passes.

To minimize the smoke formation and to burn out the carbon in the fly ash, intense overfire turbulence is necessary. High-pressure over-fire air or steam jets will certainly be required. Fortunately, the considerable experience of the U.S. boiler industry in burning wood bark, baggasse and similar materials will be very useful in designing such systems.

### b. Advantages and Disadvantages

The advantages and disadvantages discussed for waterwall incinerator systems with grate burning also apply here. The comments below concern the unique problems associated with the suspension burning concept.

*(1) Advantages.* Shredding breaks the refuse into more uniform, smaller pieces, significantly increasing the exposed surface area. When these particles are fed on top of an already-burning bed, rapid burning and improved burnout efficiency result.

Suspension-burning, aided by the turbulent mixing of fresh feed into the hot combustion gases, promotes the drying and combustion of the shredded refuse while suspended in the hot flue-gas stream.

Suspension-burning systems exhibit great sensitivity to refuse feed rate. This is advantageous in modulating the steam rate to match the steam demand. In opposition to this desirable aspect, however, is the consequent dependency upon uniform fuel characteristics. Refuse mixing to smooth perturbations in heat content may be mandatory. Larger-than-normal steam drums may be required (higher investment costs) to obtain a steady steam pressure and rate.

*(2) Disadvantages.* The dust loadings and the combustible content of the fly ash will be considerably higher than in conventional incinerators. This will require more efficient and thus costly APC systems. The vigorous mixing induced in the overfire volume, however, should minimize the formation of combustible gaseous pollutants.

Associated with this pneumatic feeding system is the necessity for a shredder to mill the refuse into the small particle sizes required for pneumatic distribution. Metal and glass separation systems will also be necessary. Both the shredding and separation equipment add to the capital costs of this system. In addition, their incremental maintenance, utilities, and labor charges add to the total operating costs of such a facility.

See also disadvantages presented above for grate-burning waterwall systems.

### c. Problem Areas

The suspension-burning concept has not yet been applied to municipal refuse disposal and, therefore, the technical risks common to new concepts must be considered. The considerable experience available on the burning of somewhat similar materials will be helpful.

Refuse feeding systems of all types have been unsatisfactory to some extent. Experiences such as bridging in hoppers and chutes, agglomeration, clogging, and other problems clearly suggest the difficulty in refuse materials handling. Pneumatic distribution systems or other continuous feed systems will undoubtedly require some development to attain acceptable, if not optimal, performance.

See problem areas presented above for grate-burning waterwall systems.

### d. Economics of Continuous-Feed, Waterwall-Construction, Suspension-Burning Incineration Systems

*(1) Capital Investment.* It is estimated that the investment costs for plants using this concept, *excluding* the capital costs associated with the milling operation, will be approximately 15% less than those for grate-burning, waterwall systems with hopper and chute feed procedures. The capital cost curves shown in Figure VII-30, therefore, should be reduced by approximately 15% prior to the incremental addition of the capital charges associated with the milling operation (Appendix A).

*(2) Total Operating Costs.* Table VII-36 shows the operating costs for a 1200-TPD incineration system with suspension burning of refuse. The system consists of two 600-TPD units operating three shifts per day, 250 days per year. The capital investment figure of $8,200,000 was developed as discussed previously and excludes the investment costs of the refuse shredding subsystem. The operating costs (including fixed costs) associated with shredding are developed in Appendix A and are shown in Table VII-36 as a modular cost. No steam credits were assumed (see Appendix F).

The unit costs for power, water, operating labor, and supervision are the same as those presented in the Introduction to Chapter VII. Overhead and maintenance costs are expressed as a percentage of labor plus supervision and capital investment, respectively. These percentages are based on engineering judgment and familiarity with similar systems in comparable service.

Table VII-36 shows that (excluding costs associated with refuse shredding), the variable costs (power and water) for this incineration system contribute approximately 11% of the total operating cost. Labor and maintenance contribute approximately 39% with the fixed costs, amortization, and interest on the loan making up the remaining 50%. The modular operating costs associated with shredding increase the total operating cost of the system by 46%.

Figure VII-31 shows the effect of rated capacity on the total operating costs of a suspension-burning system operating three shifts per day. The rated plant capacities of the horizontal axis were based on two unit furnaces each operating at 50% of plant capacity.

## TABLE VII-36

## ESTIMATED COST OF INCINERATION USING A CONTINUOUS-FEED, WATERWALL-CONSTRUCTION (SUSPENSION-BURNING) INCINERATION SYSTEM

Reference Location: Boston, Massachusetts, mid-1969 dollars
Plant Capacity: 1200 TPD (two 600-TPD furnaces)
Load Factor: 250 days per year, 3 shifts per day
Annual Consumption: 300,000 tons refuse/year
Capital Investment: $8,200,000 (excluding refuse shredding facility)

| | Units | Dollars/Unit | Units/Ton Refuse Consumed | Dollars/Ton Refuse Consumed |
|---|---|---|---|---|
| **Variable Costs** | | | | |
| Electricity | kwh | $0.015 | 22 | 0.33 |
| Water | M gal. | $0.30 | 0.5 | 0.15 |
| | | | | $0.48 |
| **Semi-Variable Costs** | | | | |
| Labor | | | | |
| 5 men per shift @ $5.00/hour | | | | 0.52 |
| 5 men per shift @ $3.00/hour | | | | 0.31 |
| 1 supervisor @ $14,000/year | | | | 0.05 |
| 1 weight scale operator @ $5,500/year | | | | 0.02 |
| | | | | $0.90 |
| Overhead @ 40% of labor and supervision | | | | 0.36 |
| Maintenance @ 1.75% of capital investment annually | | | | 0.48 |
| | | | | $1.74 |
| **Fixed Costs** | | | | |
| Amortization @ 5.2% of capital investment annually | | | | 1.42 |
| Interest on loan @ 3.0% of capital investment annually | | | | .82 |
| Sub-Total (excluding any steam credits or shredding cost) | | | | $2.24 |
| | | | | $4.46 |
| Shredding Cost (2" product top-size) | | | | 2.05 |
| Total (excluding any steam credit) | | | | $6.51 |

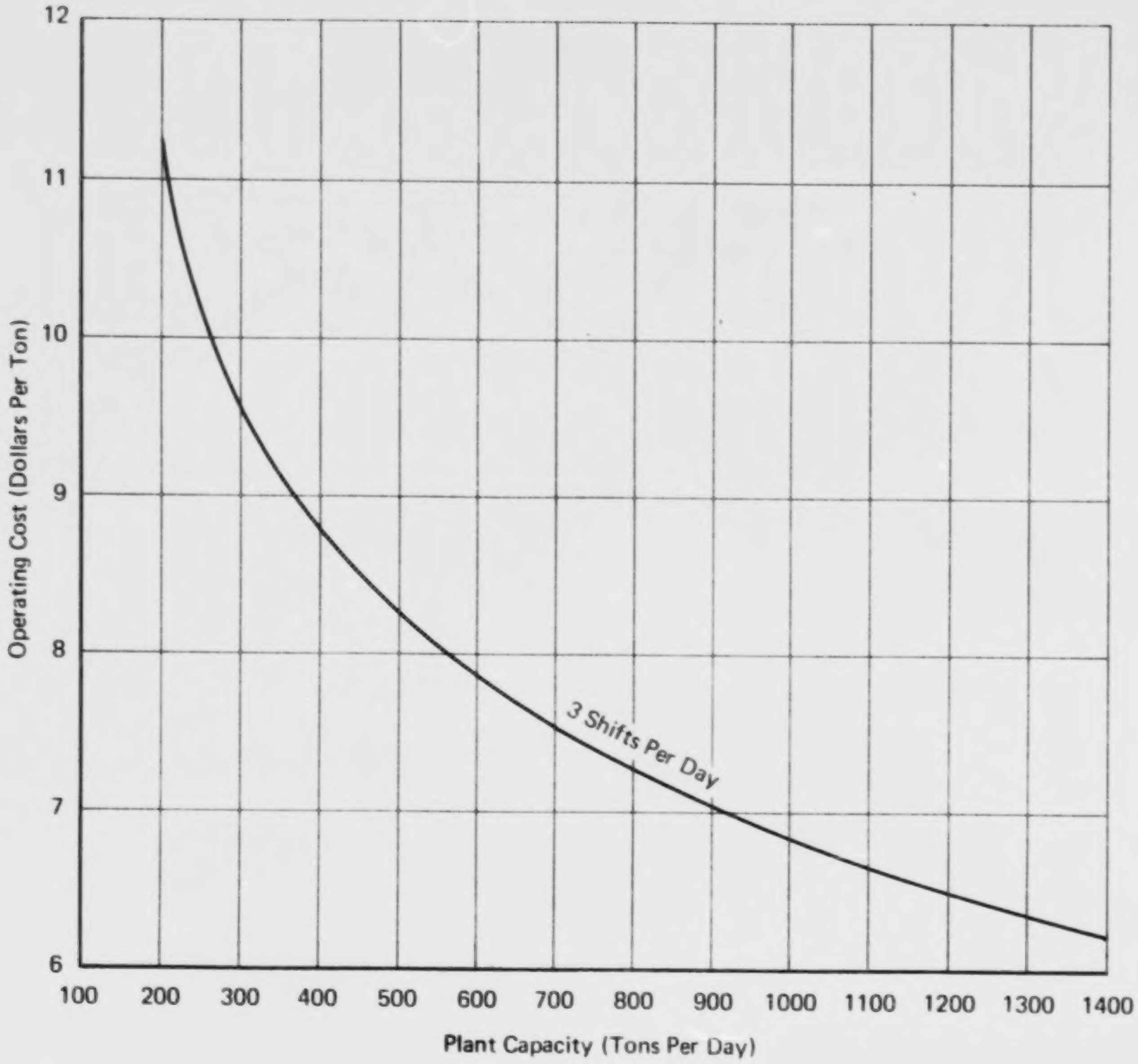


**FIGURE VII–31** TOTAL OPERATING COSTS – CONTINUOUS-FEED, WATER WALL-CONSTRUCTION INCINERATOR SYSTEMS (Suspension Burning, No Steam Credits)

Table VII-37 indicates the percent contribution of the various component costs comprising the total operating costs in Figure VII-31. These percentages were developed for three different rated plant capacities. These percentages allow for the modification of costs appearing in Figure VII-31 as discussed in the Introduction to Chapter VII and reflect assumptions other than those used to develop these component costs.

### 12. Semi-Continuous Feed: Package Incineration Systems

The concept of "package units" (prefabricated at a manufacturing facility and shipped substantially ready to operate) has been successfully applied to a number of combustion systems. Since little field work is required (except for the pouring of an appropriate concrete pad and provision of utility services), the cost and the time from order placement to facility operation are both minimized. In addition, since nearly identical units are provided, engineering costs per unit and technical risk are also reduced. A package incinerator offered by Combustion Engineering, Inc., is discussed below. The reader is cautioned, however, that this presentation is based upon estimates and evaluations made by ADL and does not reflect Combustion Engineering, Inc., policy or guarantees.

#### a. Process Description

The Combustion Engineering (CE) package incineration system shown in Figure VII-32 consists of factory-assembled modules that can be readily installed at a given site with minimal expense. These modules include the incinerator furnace, the receiving and storage building (not provided by CE), a refuse feed conveyor system, a wet scrubber APC system, stack, induced draft fan, residue handling system, and instrumentation and controls. The system, a prototype of which is now in service, is designed to handle refuse at a nominal rate of 3 TPHR or 72 TPD.

There are a number of alternate refuse handling subsystems that can be employed with the CE unit. The refuse may be dumped onto an open concrete slab with a front-end loader then loading the refuse into the charging bucket which feeds the combustion chamber. Alternatively, the refuse could be unloaded directly into a covered storage building. A front-end loader could be utilized to load a conveyor with the refuse which, in turn, feeds from the building directly into the charging bucket. For sites with different elevations, refuse could be stored on the higher elevation and loaded directly into the charging hopper positioned at the same level as the refuse dump area. Lastly, a conventional pit and crane system could be utilized (though at a comparatively high cost for new plants). The crane could deposit refuse directly from the refuse pit into the charging chute. For the economic analysis to follow, we assume that a receiving and storage building will be utilized with an associated conveyor system to load the refuse from the building to the charging bucket.

## TABLE VII-37

## DISTRIBUTION OF TOTAL OPERATING COSTS FOR CONTINUOUS-FEED, WATERWALL-CONSTRUCTION (SUSPENSION BURNING) INCINERATION SYSTEMS

(%)

| **Plant Capacity** | **200 TPD** | **600 TPD** | **1000 TPD** |
|---|---|---|---|
| **Shifts/Day** | 3 | 3 | 3 |
| **Cost** | | | |
| Power | 3 | 4 | 5 |
| Water | 1 | 2 | 2 |
| Labor and Overhead | 38 | 21 | 22 |
| Maintenance | 6 | 8 | 7 |
| Capital Charges | 29 | 36 | 34 |
| Total Shredder Operating Cost | 23 | 29 | 30 |
| Total | 100 | 100 | 100 |

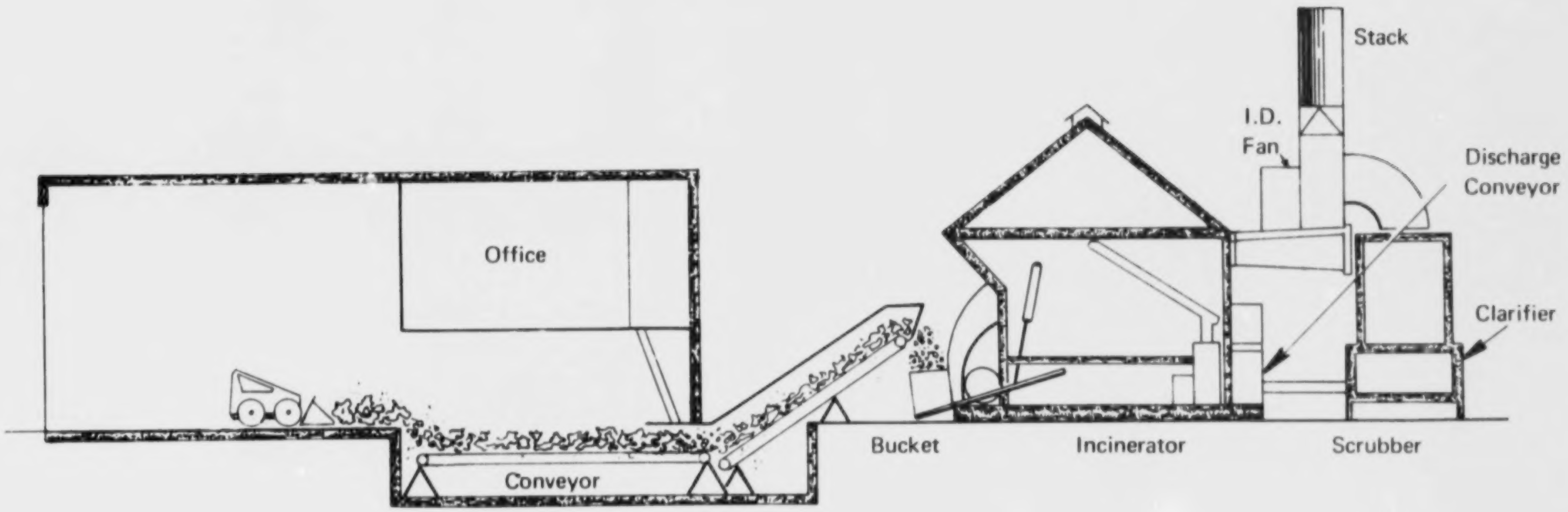

Stack
I.D. Fan
Discharge Conveyor
Office
Clarifier
Conveyor
Bucket
Incinerator
Scrubber

FIGURE VII–32 SCHEMATIC OF COMBUSTION ENGINEERING PACKAGE INCINERATOR

The incinerator chamber itself is refractory-lined and employs a four-level impact grate to move and stoke the refuse. The system is designed to operate utilizing 150-160% excess air, with the overfire-to-underfire air ratio approximately 1 to 1.

In operation, the loaded charging bucket is pneumatically raised to the combustion chamber where it drops the refuse onto the grates. The small quantity of siftings is removed periodically by hand. The refuse is leveled and advanced by the grate action and the residue falls into a quench tank. The residue removal system consists of a belt conveyor which constantly removes the residue and conveys it to containers or trucks.

The flue gases from the primary combustion chamber are deflected by a 30° angle baffle, as seen in Figure VII-32, and are redirected through a duct and into the air pollution control system (a medium-energy scrubber). An induced draft fan then discharges the cleaned flue gas through a short stack. The residue quality in the CE package unit should be comparable to that from existing continuous-feed plants.

The air pollution control potential of the CE system is difficult to assess. Because of the charging method (frequent loading of small charges) and the air seal on the charging gate, it is likely that combustible emission will not approach that of most existing batch-feed furnaces. It is probable, however, that the levels of these pollutants will exceed those of conventional continuous-feed systems. The majority of the particulate emissions, however, can be controlled with existing APC systems.

b. Advantages and Disadvantages

*(1) Advantages.* The pre-engineered package incinerator, with its relative ease of installation, requires a substantially smaller capital investment per ton of capacity relative to field-erected units.

The package unit is relatively compact, requiring less land than comparable field-erected systems.

The lower capital investment costs (reducing the fixed costs of operation), together with the limited labor force (one man is required for operation, but two men are desirable from safety considerations) and the relatively low maintenance cost required for the system result in lower operating costs relative to conventional systems of this size.

The system is designed so that the replacement of refractory elements is relatively simple. In addition, the air-cooled walls should minimize slagging problems.

*(2) Disadvantages.* The system is a package unit and therefore is not constituted of the elaborate and aesthetically pleasing buildings that are found with conventional field-erected systems. However, constructing a more attractive enclosure or using screening, if local site considerations warranted such an expenditure, could be undertaken.

The feed system, though capable of handling the great majority of refuse materials, will not accept articles which could be burned without manual or mechanical subdivision in a conventional plant. In general, however, this does not place undue restrictions on the refuse feed. Feed system problems could occur, however, if flammable fluids wet the charging bucket.

### c. Problem Areas

No serious problem areas are seen for this design subject to acceptance of its inherent characteristics regarding air pollution and residue quality.

### d. Economics of Semi-Continuous Feed, Package Incineration Systems

*(1) Capital Investment.* The cost for the Combustion Engineering package incineration system installed is estimated to be approximately $250,000. This cost includes all equipment and associated building, installation, site preparation, roadways and foundations. The costs for such a system employing an electrostatic precipitator and a coarse-spray flue gas conditioning system in place of the present scrubbing unit would cost approximately $360,000 or an additional $1,500 per ton per day.

This evaluation is based upon ADL estimates and does not reflect Combustion Engineering, Inc., policy or guarantees.

*(2) Operating Costs.* Table VII-38 shows the estimated operating costs for a 72 TPD package incineration system. The facility has one, 72 ton per day unit operating three shifts per day, 250 days per year. Table VII-39 illustrates the effects of both the number of shifts and the number of units on the total operating costs for this continuous feed package incineration system. As seen from this table, both increasing the number of shifts and the number of units tends to decrease the operating costs per ton of refuse consumed. This decrease is caused by more efficient labor utilization (with multiple units) and more efficient utilization of facilities (with multiple-shift operation).

Table VII-38 shows that the variable costs (power and water) contribute approximately 11% of the total operating costs. Labor and maintenance contribute approximately 65% with amortization and interest on the loan making up the remaining 24% of the operating costs for continuous systems.

## TABLE VII-38

## ESTIMATED COST OF INCINERATION USING A SEMI-CONTINUOUS FEED PACKAGE INCINERATION SYSTEM

| | |
|---|---|
| Reference Location: | Boston, Massachusetts, 1969 dollars |
| Plant Capacity: | 72 TPD (one, 72 TPD furnace) |
| Load Factor: | 250 days per year; 3 shifts per day |
| Annual Consumption: | 18,000 tons refuse/year |
| Capital Investment: | $360,000 |

| | Units | Dollars/Unit | Units/Ton Refuse Consumed | Dollars/Ton Refuse Consumed |
|---|---|---|---|---|
| **Variable Costs** | | | | |
| Electricity | kwh | $0.015 | 33.4 | 0.50 |
| Water | M Gal | $0.30 | 0.9 | 0.27 |
| | | | | $0.77 |
| **Semi-Variable Costs** | | | | |
| Labor | | | | |
| 1 working supervisor per shift @ $5.00/hour | | | | 1.73 |
| 1 operator per shift @ $3.00/hour | | | | 1.04 |
| | | | | $2.77 |
| Overhead @ 40% of labor and supervision | | | | 1.11 |
| Maintenance and repair @ 2.5% of capital investment annually | | | | 0.50 |
| | | | | 4.38 |
| **Fixed Costs** | | | | |
| Amortization at 5.0% of capital investment annually | | | | 1.00 |
| Interest on loan at 3.0% of capital investment annually | | | | 0.60 |
| | | | | $1.60 |
| Total Costs | | | | $6.75 |

This evaluation is based upon ADL estimates and does not reflect Combustion Engineering, Inc. policy or guarantees.

Table VII-39 presents the effects of the number of shifts and the number of units on the total operating costs for package incineration systems.

### TABLE VII-39

### THE EFFECTS OF NUMBER OF SHIFTS AND NUMBER OF UNITS ON TOTAL OPERATING COSTS FOR PACKAGE INCINERATION SYSTEMS

| Tons Consumed Per Day | No. of Units | No. of Shifts | Total Costs |
|---|---|---|---|
| 144 | 2 | 3 | 5.37 |
| 96 | 2 | 2 | 6.43 |
| 72 | 1 | 3 | 6.75 |
| 48 | 1 | 2 | 7.81 |
| 48 | 2 | 1 | 9.59 |
| 24 | 1 | 1 | 10.97 |

For a two-unit facility: labor and overhead costs in Table VII-38 would halve.

For two-shift operation: fixed and maintenance costs in Table VII-38 would increase by factor of 1.5.

For one-shift operation: fixed and maintenance costs in Table VII-38 would increase by factor of 3.

## 13. Semi-Continuous Feed: Rotary Grate Construction

### a. Process Description

A unique, rotary-grate incinerator is offered by Kennedy Van Saun Manufacturing and Engineering Corporation (KVS). This unit has a rated capacity of 3,000 lb/hr or 36 TPD, although recent experience at a full-scale plant in Shippensburg, Pennsylvania, suggests that 48 TPD may be an acceptable operating limit. For this particular system, refuse is received and stored on a 60- by 100-foot concrete floor and serviced to the incinerator by a front-end loader and hydraulic ram feeder.

The grate is fabricated of stainless steel plate, perforated with 1/2-inch holes, and shaped as a cylindrical bowl (10 feet in diameter by 5 feet high). The grate is enclosed in an uninsulated metal housing. The axis of the bowl is approximately

45° to the horizontal. The bowl continually rotates, tumbling and agitating the refuse to provide maximum exposure of the refuse to the high-temperature flue gases. The refuse is initially ignited by an auxiliary gas burner which automatically switches to "low fire" operation after satisfactory combustion temperatures have been reached. The grate may be operated over a range from 0.1 to 1 rpm.

The perforations serve to remove the fine ash particles. This effects limiting entrainment into the flue gas stream. The residue with dimensions greater than the perforations is periodically removed. This process involves stopping the feed and allowing the refuse to burn down. A door in the side of the grate is then opened and the bowl is rotated to dump the residue. The ash door is then repositioned, the feed is started, and the refuse re-ignited, utilizing the auxiliary burner. This burndown and dumping procedure takes approximately 20 minutes with the procedure repeated approximately every 2 hours.

The siftings and other residue are fed into a residue quench tank, from which a drag conveyor carries them to a collection point. The gaseous combustion products then enter a cylindrically shaped, noninsulated, stainless-steel secondary chamber where air is introduced tangentially near the bottom. This secondary chamber has two zones. One zone has relatively cool air spiralling up just inside the cylinder wall. At this point, the combined updraft and centrifugal action precipitate the larger particles from the exhausting gases and drop them back to the grate below. In the other zone (central), moderate turbulent mixing occurs and combustion of combustible particulates and gases takes place.

The gases next enter a 35,000-cfm wet scrubber where they are cooled to 170°F and are then passed into the induced draft fan and out the stack. To avoid corrosion problems, the scrubber effluent is treated with ammonia before recycle.

To provide a consistent basis for comparison with other incineration systems, a dry-bottom, flue gas cooling system and electrostatic precipitator were substituted for the scrubber in the following economic analysis.

The residue quality from this system can be quite adequate, depending heavily upon the operator and the degree of burnout of the siftings. However, the performance of this system relative to residue quality is presently unknown.

The furnace particulate emission level for this system is also uncertain. The ram-feed system provides an air lock which, in combination with the auxiliary burner, should contribute to an efficient burnout of combustible pollutants. The perforated grate may reduce mineral particulate. We speculate that the furnace emission rate will fall between those for existing batch and continuous-feed systems.

b. Advantages and Disadvantages

*(1) Advantages.* The tumbling action of the rotating grate breaks open refuse agglomerates and results in excellent heat transfer to the bed. The refuse bed temperatures are expected to be relatively uniform, resulting in more efficient burnout.

The grate design with relatively large perforations passes the smaller particles but provides additional retention time to permit complete burnout of large pieces of combustible refuse.

The rotational speed of the grate can be varied to provide flexibility of operation.

The secondary chamber is designed to provide the turbulence required for adequate mixing of the flue gas and, therefore, the elimination of noxious gases and combustibles from the flue gas stream. The use of the auxiliary burner to maintain combustion conditions, though costly, aids in avoiding combustible pollutant emissions.

The relatively simple construction of this unit contributes to low capital investment per TPD installed capacity for its capacity class.

*(2) Disadvantages.* This system is basically a batch-feeding system which results in a cyclic variation in the characteristics of the refuse bed and the particulate and volatile materials in the cone and secondary chamber. The savings in gas composition are minimized, however, by frequent charging of small weights of refuse. This surge of pyrolysis products may overwhelm the constant air supply, resulting in an increase in the quantity of combustible particulates and gases being emitted from the secondary chamber.

The perforated-steel cylindrical grate is subjected to the corrosive atmosphere existing in incinerator furnaces. Its life expectancy is not expected to exceed 3 to 5 years.

The absence of refractories results in high furnace heat loss and some unnecessary auxiliary burner fuel consumption. The furnace is well suited to intermittent operation, however, as a consequence of the small "thermal inertia" in the metal walls. In future installations, it has been suggested that refractory could be installed in the secondary chamber.

See also disadvantages for batch-feed systems.

c. Problem Areas

This incineration concept is new with only one facility in commercial operation. Although operation of this plant has to date been acceptable, the facility has been onstream for less than one year which is not sufficient time to evaluate its performance fully. This concept, therefore, is subject to the risks and unknown situations and problems accompanying new and relatively untested systems.

A problem common to conventional grates – plugging – has not been of significant concern at the KVS facility at Shippensburg, Pennsylvania. However, depending upon the nature of the refuse, plugging represents a potential problem. Metal foils, plastics, and glass, for example, could fuse to the grate, resulting in plugging of the perforated holes. Further plant operation with varying compositions of refuse may be necessary to substantiate whether plugging is, indeed, a potential problem.

During operation of the Shippensburg facility, some problems were encountered with fires in the ram feeder. This problem is reported to have been solved by using a longer ram stroke and installing a guillotine isolation gate.

See also problem areas for batch feed systems.

d. Economics of Semi-Continuous Feed, Rotary Grate Construction Incineration Systems

*(1) Capital Investment.* Based on ADL estimates and review of public information regarding this system, we estimate that a twin furnace, 72 ton per day incineration facility, consisting of two, 36 ton per day units would cost approximately $630,000 for plants built in mid-1969, location Boston, Massachusetts. These costs include the two incinerator units and related process equipment, the buildings, refuse storage bin, and front-end loader, water treatment facilities, electricity, piping, controls, storage, and electrostatic precipitator and associated ducting. The costs of the electrostatic precipitator were based on 200% excess air at the stack.

We estimate that the cost of incremental rotary bowl units of 36-TPD capacity, including all the costs associated with the subsystems, building, and land preparation, would approximate $315,000.

This presentation is based on ADL estimates and in no way reflects the policy or guarantees of the Kennedy Van Saun Corporation.

*(2) Operating Costs.* Table VII-40 shows the operating costs for an incineration facility consisting of two 36-TPD rotary grate units. The capital investment figure of $630,000 was developed from the preceding discussion of investment costs. Utilities and labor requirements are based on public data regarding an existing system at Shippensburg, Pennsylvania.

Table VII-40 shows that only two operators are needed per shift to operate this facility. The labor plus overhead and maintenance, which make up the semi-variable costs, contribute approximately $4.75 per ton of capacity per day, or approximately 56% of the total operating costs. The fixed costs, consisting of amortization and interest on the loan, total $2.81 per ton per day of capacity or approximately 33% of the total operating cost. The remaining 11% is comprised of the variable costs (water, power, and auxiliary fuel).

This presentation is based on ADL estimates and in no way reflects the policy or guarantees of Kennedy Van Saun Corporation.

### 14. Continuous-Feed Systems: with Residue Fusion

One of the primary objectives of incineration is the reduction of solid waste volume. A second objective is the production of a residue material which is nonputrescible, noncombustible, biologically sterile, and, if possible, usable as a stable fill material. All of the concepts described above approach these objectives. The ultimate in residue quality, however, is obtained when the residue is fused. A more detailed description of the fusion or "slagging" process is presented in section VII.D.; a description of advanced incineration developments based on this principle is also included there. At the present time, however, the only system of this type proven over several years of operation (industrial waste only) is the FLK incinerator offered by the Dravo Corporation. The description and economics presented below are addressed to the FLK system. This presentation is based upon estimates and evaluations made by ADL, and it does not reflect Dravo policy or guarantees.

#### a. Process Description

A diagram of the Dravo/FLK incinerator is presented in Figure VII-33. Refuse from the pit is loaded by crane into feed hoppers and passed through breakers to ensure that the size of the refuse components are compatible with the dimensions of the annular "feed chute." If the incinerator is to receive bulky refuse, a separate refuse pit, together with a shredder, would be necessary. These additional subsystems related to the handling of bulky refuse will not be considered in the analysis to follow. Other techniques of refuse storage and feeding, such as a refuse bin and conveyor system, might also be applicable, but will not be

## TABLE VII-40

## ESTIMATED COST OF INCINERATION USING A SEMI-CONTINUOUS FEED, ROTARY-GRATE CONSTRUCTION INCINERATION SYSTEM

| | |
|---|---|
| Reference Location: | Boston, Massachusetts, 1969 dollars |
| Plant Capacity: | 72 TPD (two 36-TPD furnaces) |
| Load Factor: | 250 days per year; 3 shifts per day |
| Annual Consumption: | 18,000 tons refuse/year |
| Capital Investment: | $630,000 |

| | Units | Dollars/Unit | Units/Ton Refuse Consumed | Dollars/Ton Refuse Consumed |
|---|---|---|---|---|
| **Variable Costs** | | | | |
| Electricity | kwh | $0.015 | 18.3 | 0.27 |
| Water | M gal | $0.30 | 0.60 | 0.18 |
| Fuel | MM Btu | $0.80 | 0.63 | 0.50 |
| | | | | $0.95 |
| **Semi-Variable Costs** | | | | |
| Labor | | | | |
| 1 front loader operator per shift @ $5.00/hour | | | | 1.73 |
| 1 residue removal man per shift @ $3.00/hour | | | | 1.04 |
| | | | | $2.77 |
| Overhead @ 40% of labor and supervision | | | | 1.11 |
| Maintenance and repair @ 2.5% of capital investment annually | | | | 0.87 |
| | | | | 4.75 |
| **Fixed Costs** | | | | |
| Amortization @ 5.0% of capital investment annually | | | | 1.75 |
| Interest on loan @ 3.0% of capital investment annually | | | | 1.06 |
| | | | | 2.81 |
| Total Costs | | | | 8.51 |

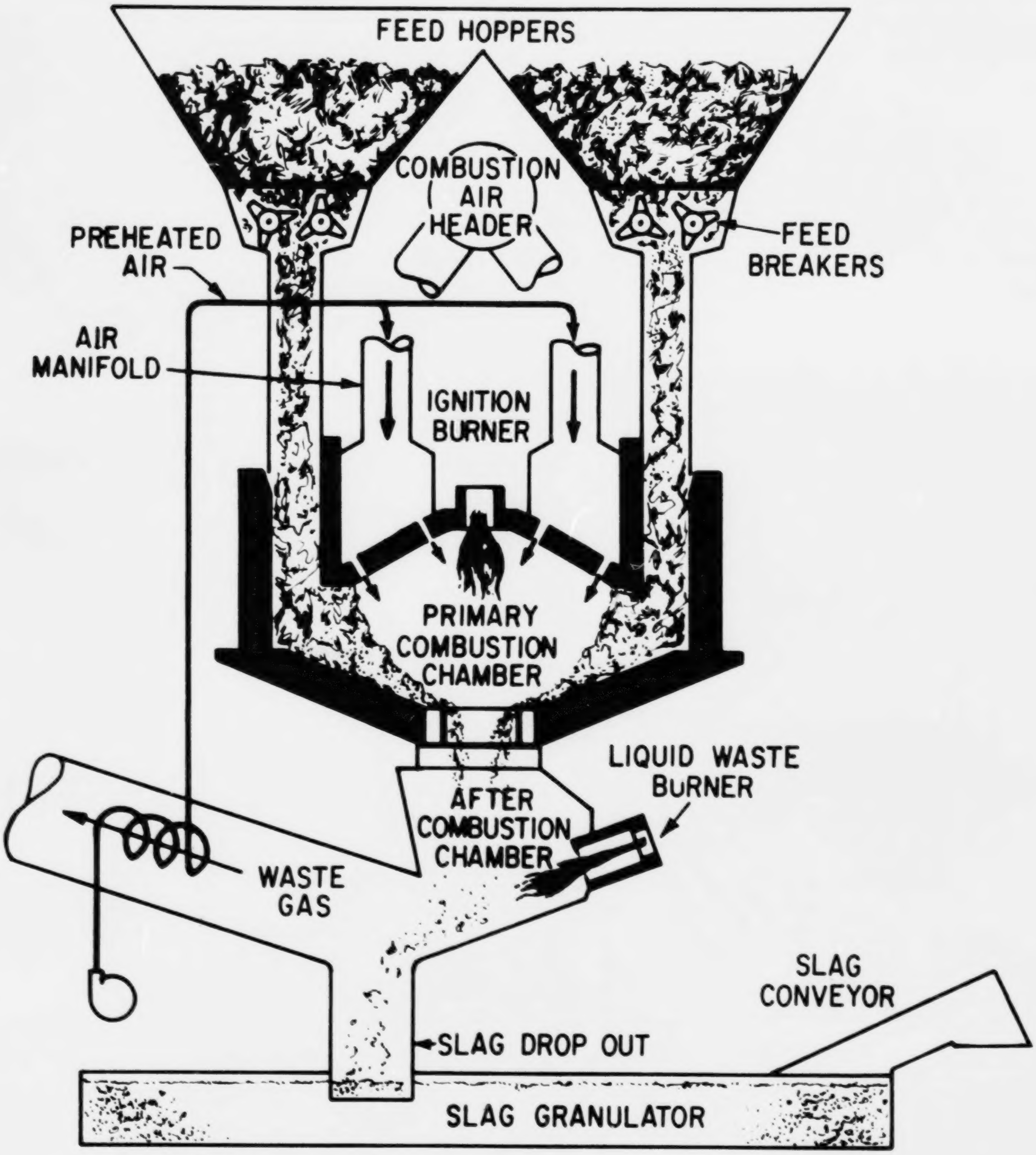

FEED HOPPERS
COMBUSTION AIR HEADER
PREHEATED AIR
FEED BREAKERS
AIR MANIFOLD
IGNITION BURNER
PRIMARY COMBUSTION CHAMBER
LIQUID WASTE BURNER
AFTER COMBUSTION CHAMBER
WASTE GAS
SLAG CONVEYOR
SLAG DROP OUT
SLAG GRANULATOR

FIGURE VII–33 DRAVO/FLK INCINERATOR

considered here either. The annular feed chute is formed between the inner shaft and an outer cylindrical shell. The top section of the outer shell rotates to distribute the refuse evenly. The refuse in the annular chute acts as a seal to avoid air infiltration.

The refuse drops through the chute by gravity as material burns out in the combustion zone. As the waste material approaches the combustion zone, it is moved forward by rotation of the furnace bottom. Primary air enters the combustion chamber through nozzles located in the upper dome. An oil- or gas-fired burner in the center of this upper dome is available to ignite the refuse. The burner is normally operated only until the heat released by the combustion of the waste is sufficient to maintain slag fluidity. Under special conditions, such as low refuse heating value, the burner can be ignited to maintain appropriate temperature levels.

The rapid combustion of the wastes with preheated air develops a primary chamber temperature of 2400° to 2600°F. The resulting slag runs down through the water-coated discharge port or "monkey" located at the bottom of the combustion chamber; through the after-combustion chamber; and into a quench-water tank below. A drag conveyor carries the granulated slag out of the tank.

The air and combustion gases from the primary chamber pass into the after-combustion chamber where additional preheated air is provided to ensure complete combustion. Unburned materials incidentally falling through the port into the after-combustion chamber will be burned with the noncombustibles melting under the influence of the hot gas stream from the primary chamber.

This concept can also dispose of liquid waste materials, such as oil sludges and chemicals. Burners located in the after-combustion chamber would be utilized for this purpose. These burners also serve to preheat the after-combusion chamber during startup prior to the startup of the ignition burner in the primary combustion chamber.

The hot gases leaving the after-combustion chamber pass through a duct to a heat exchanger where the combustion air is preheated. The balance of the heat in the flue gas may be recovered by utilizing a waste heat boiler system, or the gases may simply be cooled with no energy recovery. The gases are then cleaned in a precipitator, scrubber, or other air pollution control device, and pass through the induced draft fan to the stack. For the economic analysis to follow, we assumed that no waste heat recovery system was utilized, but that a water spray arrangement was provided to cool the gases prior to entering the electrostatic precipitator.

An FLK system has been built and is now operating at the Wolfsburg plant of Volkswagen in Germany. The unit has been improved during its more than two years of operation and reportedly is performing well on both domestic refuse and the industrial refuse generated within the plant. Waste oils are burned in the secondary combustion chamber. Compared to U.S. refuse, the feed to the VW unit has been generally high in calorific content and, to an extent, has been more consistent in composition. Also, the burning of waste oils has aided in maintaining slag fluidity in the secondary chamber. Although some changes in design and in operating practices will probably be required for municipal refuse feed, the fundamental furnace concept has been well demonstrated.

As described above, the residue quality of the FLK and other slagging concepts should be superior to that of any conventional grate-burning plant. The residue will be sterile and biologically inert. Sizing and crushing should yield a material suitable for backfilling and, perhaps, as a concrete aggregate. It may also be possible to recover ferrous metal values.

The air pollution control potential of the FLK unit is difficult to assess. It has been suggested that fly ash loadings at the entrance to the APC system will approximate two times those found in conventional plants. The system appears to provide mixing levels and to operate at temperatures which should burn out much of the combustible pollutants. It is speculated that nitrogen oxide emission could be increased in comparison with conventional incinerators. No test data, however, are available.

b. Advantages and Disadvantages

*(1) Advantages.* The residue from the Dravo/FLK system contains no unburned or putrescible materials. In fact, it is a sterile, odorless slag that can be deposited without hazard to public health.

This residue slag is a fine granular material that makes a very satisfactory landfill with little generation of dust.

The volume reduction of refuse to slag residue was estimated at 94% to 98% which is highly satisfactory relative to conventional incinerator systems.

The system will incinerate almost all types of refuse materials that can be physically handled, including larger wood or metal materials.

The absence of grates alleviates the problems commonly associated with grate systems.

Because there are no moving grates or other metal parts in direct contact with the burning refuse, the temperature limitations normally imposed by these metals are eliminated in this concept. Less quantities of excess air are therefore required.

The high temperature and lower excess air levels result in more efficient heat transfer for potential waste heat recovery systems and smaller, less expensive, air pollution control devices.

See also advantages for continuous-feed, rectangular construction.

*(2) Disadvantages.* Because of the comparatively complex nature of the Dravo/FLK design, a better trained and more highly qualified operating and supervisory staff will be required.

The sophisticated nature of the system may require a more rigorous preventive maintenance program than is found in most conventional systems.

The complex design associated with the Dravo/FLK system increases its investment costs relative to conventional systems.

Continuous operation of slagging systems depends upon slag fluidity. Highly refractory refuse components or surges of wet refuse could, therefore, cause thickening of the slag and temporary restriction of the primary furnace outlet. Combustion control systems (especially regarding fan pressure and auxiliary fuel burning) must be able to cope with these effects.

Auxiliary fuel consumption, in excess of that required for ignition, may be required when the refuse is of low calorific value. Air preheating reduces this cost (although it increases investment and fan power costs), but may be insufficient for very wet refuse.

c. Identification of Problem Areas

High temperatures of 2800 to 3100°F significantly test the integrity of construction materials. Under these thermal loads and slagging conditions, refractory materials may flux and/or spall. Waterwalls which are successfully used in boilers where flame temperatures commonly reach this level are utilized in the after-combustion chamber, where they are protected by the chilled slag layer which forms. The refuse bed serves as an effective insulation for the primary combustion chamber. The most vulnerable area is the refractory roof on the primary chamber. It is believed, however, that following several modifications, this problem has been solved.

The friction between the walls of the annular feed chute and the refuse materials may hinder the downward movement of the refuse into the primary chamber. To act as an effective air seal, the refuse should be packed to some extent, creating the possibility of bridging in sections of the annular shaft. The breakers, however, which limit the size of refuse materials entering the unit, together with the rotating upper shaft and rotating bottom of the primary chamber, should substantially eliminate this potential problem.

Because of the extreme temperatures in the monkey and after-combustion chamber, the need for water cooling is vital. Any discontinuation of water supply could cause serious damage to the water-cooled walls and supports of the furnace. It is, therefore, necessary to employ the same precautions and operating practices utilized with boilers, i.e., a reserve water supply and stand-by spare water pumps.

This concept has been demonstrated in full-scale equipment, but the experience to date has been with industrial waste. Although it is felt that the transition in feeds can be made, the furnace should be tested on U.S. municipal solid waste. Some problems may be revealed in such tests relative to slag fluidity (the need for fluxing aids) and auxiliary fuel requirements.

### d. Economics of Continuous-Feed Incineration Systems with Residue Fusion

*(1) Capital Investment.* Very limited information is presently available concerning the capital investment for the Dravo/FLK slagging incinerator. A recent brochure issued by Dravo presents a preliminary investment estimate of $2,400,000 or approximately $16,000 per TPD for a 150-TPD system, including waste heat boiler, electrostatic precipitator, building, and site preparation. To compare the economics of this system with the other concepts, the estimated costs associated with the waste heat boiler were eliminated. A spray quenching system was substituted to cool the flue gases to 600°F. The resulting facility, comprising two 150-TPD Dravo/FLK units, is estimated to cost approximately $4,000,000. In this estimate, we assumed that the costs related to the second unit and its related building and subsystems will be approximately equal to the costs associated with the first unit. We feel that, although there may be some savings on incremental units from such items as less additional square footage requirements and more efficient construction labor and equipment utilization, these savings are variable and their impact on investment costs and, more importantly, on the total operating cost, would be small.

This evaluation is based upon estimates and evaluations made by ADL and does not reflect Dravo policy or guarantees.

*(2) Total Operating Costs.* Table VII-41 shows the estimated operating costs for a 300-TPD Dravo/FLK slagging incineration facility. The facility has two 150-TPD units and operates three shifts per day, 250 days per year. Unit costs for power, water, operating labor, and supervision are the same as those presented in the Introduction to Chapter VII. Overhead and maintenance costs were expressed as a percentage of labor plus supervision and capital investment, respectively. These percentages were based on engineering judgment and analysis of the concept.

Table VII-41 shows that the variable cost, i.e., the costs for power and water, contribute approximately 17% of the total operating cost. Labor and maintenance contribute approximately 38% with amortization and interest on the loan making up the remaining 45% of the operating costs for continuous systems.

This evaluation is based upon estimates and evaluations made by ADL and does not reflect Dravo policy or guarantees.

### 15. Summary

The preceding analysis of incineration concepts, based on existing technology, indicates the range of system characteristics which can be obtained. Because of the widely differing requirements in various communities, selection of an "optimum" system is inappropriate without specific knowledge of local municipal needs. Table VII-42 summarizes, however, the characteristics of the various concepts on a relative scale of 1 (highly unfavorable) to 5 (highly favorable). Value judgments made in preparing this table were based on the technical and economic analysis presented above and the discussion and analysis of air pollution emission data presented in Chapter V.

Table VII-42 clearly shows the diversity of incinerator performance available in new incinerator systems. In all cases, the mineral particulate furnace emissions associated with the various concepts are controllable, using existing APC systems, but the cost (efficiency requirement) varies. Differences in combustible gaseous and particulate furnace emissions, evident in the existing plants which served as the basis for the ranking, may be reduced or eliminated through the development of improved furnace design and combustion control techniques. As a result, the relative ranking of the concepts may change in the future for this aspect of performance. Changes in other criteria of performance are unlikely without very major changes in the design and operating basis.

The concepts discussed in this portion of the report are all based on well-proven technology, either in incineration or other facets of modern combustion practice. In the following discussion (VII.E.), concepts which build upon and branch out from these existing techniques are discussed to establish new standards of performance.

## TABLE VII-41

## ESTIMATED COST OF INCINERATION USING A CONTINUOUS-FEED WITH RESIDUE FUSION INCINERATION SYSTEM

| | |
|---|---|
| Reference Location: | Boston, Massachusetts, 1969 dollars |
| Plant Capacity: | 300 TPD (two 150-TPD furnaces) |
| Load Factor: | 250 days per year; 3 shifts per day |
| Annual Consumption: | 75,000 tons refuse/year |
| Capital Investment: | $4,000,000 |

| | Units | Dollars/Unit | Units/Ton Refuse Consumed | Dollars/Ton Refuse Consumed |
|---|---|---|---|---|
| **Variable Costs** | | | | |
| Electricity | kwh | $0.015 | 36.8 | 0.55 |
| Water | M gal. | $0.30 | 0.9 | 0.27 |
| Natural Gas | MM Btu | $0.80 | 1.0 | 0.80 |
| | | | | $1.62 |
| **Semi-Variable Costs** | | | | |
| Labor | | | | |
| 1 crane operator per shift @ $5.00/hour | | | | 0.42 |
| 1 furnace operator per shift @ $5.00/hour | | | | 0.42 |
| 1 charging floor man per shift @ $3.00/hour | | | | 0.25 |
| 1 residue man per shift @ $3.00/hour | | | | 0.25 |
| 1 supervisor @ $14,000/year | | | | 0.19 |
| 1 weigh scale operator @ $5,500/year | | | | 0.07 |
| | | | | $1.60 |
| Overhead @ 40% of labor and supervision | | | | 0.64 |
| Maintenance and repair @ 2.5% of capital investment annually | | | | 1.33 |
| | | | | $3.57 |
| **Fixed Costs** | | | | |
| Amortization @ 5.1% of capital investment annually | | | | 2.72 |
| Interest on loan @ 3.0% of capital investment annually | | | | 1.60 |
| | | | | $4.32 |
| Total Costs | | | | $9.51 |

## TABLE VII-42

## SUMMARY EVALUATION OF INCINERATION CONCEPTS BASED ON EXISTING TECHNOLOGY

| | Criteria Of Performance | | | | | | |
|---|---|---|---|---|---|---|---|
| | Furnace Emissions | | | | | | |
| | Mineral Particulate | Combustibles | Reliability | Residue Quality | Safety | Cost | Potential For By-Product Credits |
| Batch Feed | | | | | | | |
| • Rectangular and Cylindrical | 4 | 1 | 4 | 2 | OK | 4 | – |
| Continuous-Feed | | | | | | | |
| • Rectangular Construction | 3 | 3 | 3 | 3 | OK | 3 | – |
| • Horizontal-Cylindrical Construction | 3 | 3 | 3 | 3 | OK | 3 | – |
| • Ignition Grate plus Burnout Kiln | 2 | 4 | 3 | 4 | OK | 2 | – |
| • Volatilizing Kiln and Burnout Grate Construction | 3 | 3 | 4 | 4 | OK | 2 | – |
| • 3-Stage, Rotary-Kiln Construction | 2 | 3 | 4 | 4 | OK | 2 | – |
| • Waterwall Construction (Grate Burning) | 4 | 4 | 5 | 3 | OK | 2 | Yes |
| • Waterwall Construction (Suspension Burning) | 2 | 5 | 5 | 4 | OK | 2 | Yes |
| Semi-Continuous Feed | | | | | | | |
| • Package System | 3 | 3 | 3 | 3 | OK | 5 | – |
| • Rotary Grate | 2 | 3 | 3 | 3 | OK | 4 | – |
| Continuous Feed with Residue Fusion | 2 | 4 | 3 | 5 | OK | 3 | – |

**Range:** 1 = highly unfavorable; 5 = highly favorable.

## E. TECHNO-ECONOMIC ANALYSIS – INCINERATION CONCEPTS BASED ON ADVANCED TECHNOLOGY

The people of the United States have traditionally prided themselves on their innovative exploitation of technology for the material betterment of their lives. In few cases is the need for technological advancement more pressing than in the area of solid waste disposal. The need, felt throughout the technical and business communities, has resulted in the postulation of a wide variety of new disposal concepts, including compaction with railhaul, ocean dumping, biochemical treatment, by-product recovery, composting, and a number of incineration concepts.

### 1. Introduction

The U.S. Department of Health, Education and Welfare, acting through the Bureau of Solid Waste Management and the National Air Pollution Control Administration (NAPCA), is now engaged in the evaluation of many of these alternatives. In line with the special mission of NAPCA, an analysis of the potential technical and economic features of new combustion-oriented concepts, as they impinge upon future U.S. incinerator air pollution emissions, is presented in this section. A general evaluation of the advantages, disadvantages, and problem areas of the proposed incineration system, as they are reflected in the five criteria of incinerator performance (section D of Appendix H), is also presented.

For each incineration concept discussed, a description of the distinguishing technical features of the process is presented, together with the advantages and disadvantages inherent in the system concept. Problem areas which indicate weaknesses or potential problems not inherent in the concept are also discussed; those which appear amenable to engineering development or research are cited. An economic analysis of each concept, covering both the anticipated investment costs as well as the estimated total operating costs for these concepts, is developed. Where appropriate, tables and figures are utilized to illustrate the influence and sensitivity of such variables as economics of scale and labor requirements on total operating costs.

All plants are evaluated on the assumption that they have the same APC system (99% efficient electrostatic precipitators). It should be noted that this is *not* an evaluation at the same level of emission. By this means, however, the costs associated with the APC system may be readily subtracted from the costs for any of the systems discussed using a single value for similar capacities and operating schedules. (These APC costs may be computed from the data presented in Chapter VII, B.7.) Alternatives can then be substituted.

In a sense, this evaluation is disappointing. In general, the concepts are extensions of current practices in incineration or in the pyro-processing and chemical industries. While this is fortunate from the viewpoint of shortening the development time required, no *major* new developments covering all five of the criteria of performance are foreseen. In the specific area of incinerator air pollution, however, concepts based on refuse pyrolysis appear to offer an opportunity for substantial reductions in combustible emissions and flue gas volume. Concepts involving residue fusion produce the ultimate in refuse volume reduction and sterilization.

### 2. Limitations

Few of the concepts discussed in this section of the report have been demonstrated in working pilot plants. Of those now under test, only a fraction have operated under realistic conditions or for prolonged durations. As a result, the identification of technical problems and the estimation of investment and operating economics are necessarily speculative. The contents of this portion of the report, therefore, often reflect engineering judgments, rather than fact. Perhaps in no area is the potential for error as great as in the economic analysis. The economic evaluations are not based on detailed cost estimates of specific plant designs. Instead, economic data presented in sections VII.C. and VII.D were utilized in combination with appropriate estimates from brochures, the open literature, or from similar systems used in the chemical or metallurgical processing industries.

### 3. Scope and Approach

Incineration concepts considered in the category of advanced technology are those which have not yet reached a stage of development justifying construction of a full-scale demonstration unit as the next appropriate step in process evaluation. Stages of development vary from conceptual design to pilot plant studies. Evaluation of these advanced concepts was made on a generic basis; that is, broad concept categories were treated and major variations on the basis concepts examined. Minor variations peculiar to specific hardware systems were not considered in detail.

The categories of advanced concepts are:

- *Slagging Incinerators.* Involving either combustion of refuse at temperatures above the ash slagging temperature (Type I) or fusion of the ash as an additional unit operation with more conventional incineration (Type II). Most approaches use a supplemental energy source to reach and maintain slagging temperatures.

- *Fluidized Bed Incinerators.* Applying fluidized, bed-combustion technology for incineration of solid waste. In general, pretreatment of the refuse is necessary (shredding, metal removal, etc.).

- *Pyrolysis.* Involving the autogenous thermal decomposition of refuse to produce combustible organic gases, liquids, and char.

### 4. Slagging Incinerators

#### a. General Technology and Process Description

The principal technical advantages of approaches utilizing slagging techniques are:

- maximum volume reduction of solid waste (approximately 95%);

- complete combustion or carbonization of all putrescible matter by reducing the refuse residue to a melt to produce a sterile, compact material (suitable as a high-quality fill).

These advantages, unique to slagging systems, are limited to the incinerator performance criterion of residue quality. Other criteria of performance (Appendix H) are met by the various embodiments of the slagging concept, but generally only to a degree equal to or less than that found for modern, continuous-feed systems. As a result, slagging concepts may have particular significance to communities with limited residue disposal land holdings, or when local situations suggest a revenue-producing market for the residue material (such as use for fill in parts of Florida).

Melting of the incombustible residue can be accomplished by either incineration of the refuse above the residue slagging temperature (Type I) or fusion of the ash in an additional unit after more conventional incineration (Type II). Temperatures in excess of 2600-2800°F are required. The minimum temperature required depends upon the metal content and composition of the refuse; to ensure adequate melt fluidity, a temperature of about 3000°F is sometimes needed. Some processes utilize limestone or fluorspar additives as a flux to aid fusion and fluidity.

In conventional, grate-type refractory incinerators, the furnace temperature is kept below 1800-2000°F by the introduction of excess air to avoid fluxing of refractories by fly ash components, to reduce fly-ash adherence, and to minimize refractory maintenance. About 100% excess air is theoretically required to obtain these temperatures for refuse containing 25% moisture. Air inleakage and poor air utilization (inadequate mixing) increase the total air requirement to levels considerably above 100% excess.

In theory, refuse of less than 25% moisture could be burned in a special furnace to produce temperatures of 3000°F by operation under or near stoichiometric conditions (0-20% excess air). By implication, such conditions could not be maintained in a conventional furnace because of the operational problems described above. The ability to attain such temperatures depends upon the following factors:

- usable refuse heating value;
- refuse moisture, metals and content of inert material;
- excess air level required for complete combustion; and
- availability of supplemental energy sources.

The results of a detailed energy balance for the slagging situation (as represented in Figure VII-34) reveal the relationship among these variables. The figure shows the supplementary heat input required to maintain the combustion chamber at 3000°F, as a function of the amount of excess air used, for various levels of refuse moisture (and corresponding heating value). The calculations and the resulting figure were based on the reference refuse composition presented in Appendix C, on the assumption of 10% oxidation of metals and 100% oxidation of other combustible. At higher or lower moisture levels, changes were made proportionately in combustible, ash, and metal content. The stoichiometric air requirement was assumed to be 6.34 pounds per pound of combustible material, and the residue heat capacity and heat of fusion were assumed at 0.23 Btu/lb °F and 110 Btu/lb, respectively.

Figure VII-34 also shows that supplementary heat is required to maintain slagging temperatures over almost the entire range of refuse content investigated. Only the driest material, burned with less than 10% excess air, can sustain a furnace temperature of 3000°F with no additional heat input. It is unlikely that complete combustion can be realized with only 10% excess air, however, due to inadequate mixing. The energy balance calculations discussed above were based upon an idealized case of complete combustion, perfect mixing, and thermal equilibrium in the furnace. However:

- temperature differences exist;

- system design may be such that complete combustion does not occur in the primary combustion chamber;

- low excess air levels, or reducing environments, can be maintained in the primary chamber, with combustion completed in a secondary chamber;

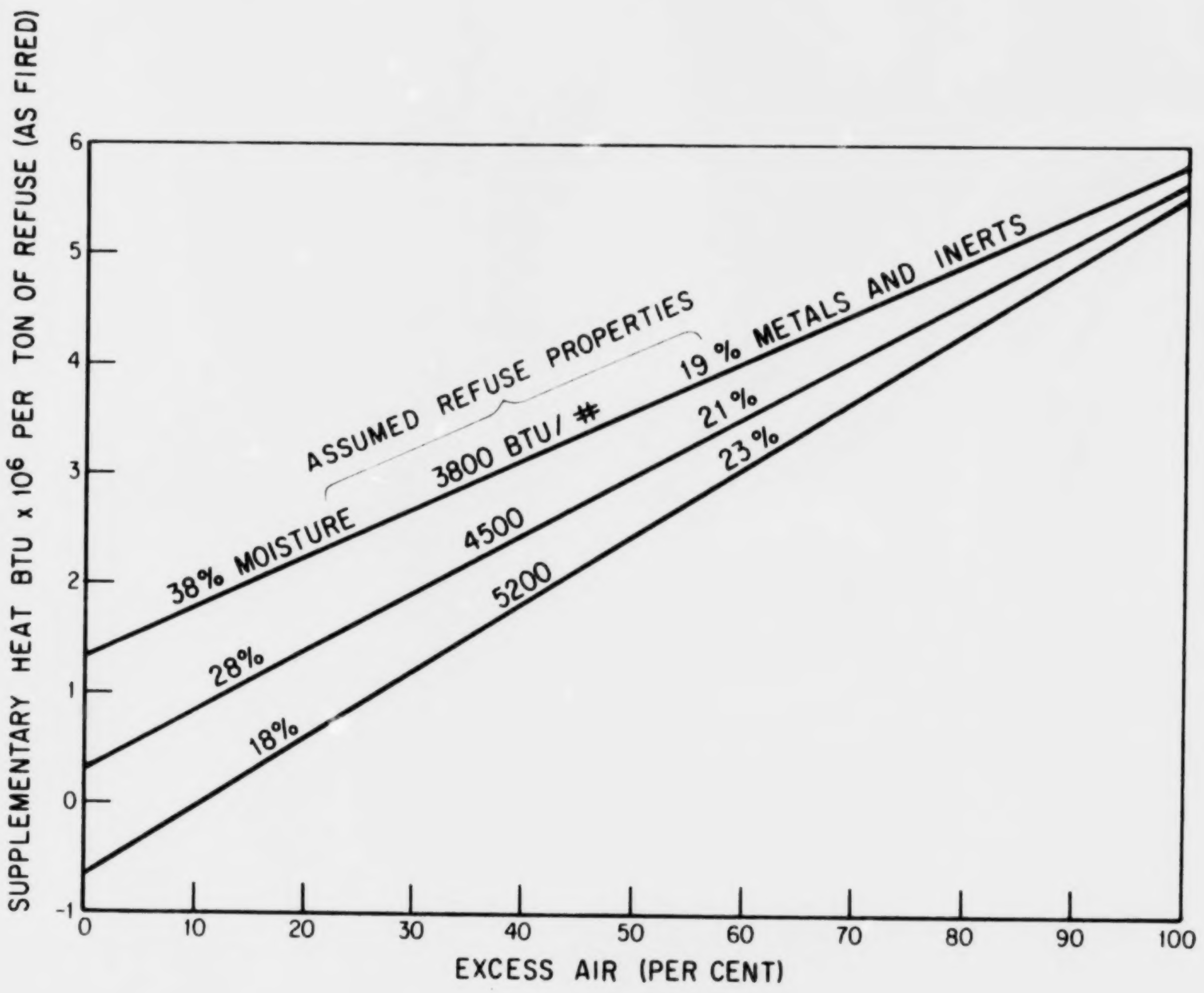


FIGURE VII–34 SUPPLEMENTARY HEAT REQUIREMENT FOR ASH FUSION AT 3000°F

- the entire chamber need not be at 3000°F, but only the portion of the system where slagging occurs.

These energy balances, however, are useful to estimate the performance of systems in which slagging occurs in the furnace (rather than in a relatively isolated supplementary operation) where the overall temperature will vary with the degree of completion of combustion and the quantity of air used. As an example, the Dravo/FLK incinerator discussed in section D is reported to require a heat input of 1.26 MM Btu/ton of refuse (at 20% moisture and 20% inerts) burned with 25% excess air. This heat input (provided by combustion air preheat) agrees well with the value of about 1.1 MM Btu/ton interpolated from Figure VII-34.

If the solid combustion residue is slagged after conventional incineration, leaving the grate at, say, 1700°F, only the sensible heat required to bring the solids from 1700°F to slagging temperature and the heat of fusion of the residue need be supplied as supplementary energy. The energy required is about 409 Btu/pound of inert material, or 180 M Btu/ton of refuse at 22% inerts, regardless of the refuse moisture level.

Various approaches have been suggested to apply the slagging concept, including systems utilizing:

- heat recuperation for preheat of combustion air or auxiliary fuel (Dravo/FLK);
- coke or natural gas, or both, in the combustion chamber (Melt-Zit Process, American Thermogen Division of Process Plants Corporation);
- combustion air preheated in a gas-fired refractory heat exchanger (Torrax);
- oxygen-enriched air;
- a grate-type primary combustion chamber for partial burnout and carbonization of combustibles followed by a coke-fired, cupola-type furnace for slagging of the residue from the grate (Ferro-Tech);
- an electric arc furnace for slagging normal incinerator residue (ADL); and
- combustion air preheated by recuperation, operating on refuse from which most metal and glass have been removed (Sira).

The above processes differ in the sequence of refuse combustion and slagging steps and in the method of supplying the supplemental energy. They are in various stages of development from full-scale demonstration units to process concepts. A plant has been built using the FLK design; consequently, this process was treated in detail in section VII.D. The other concepts are discussed individually below. Many of the processes in this category share process advantages, disadvantages, problem areas, and economics. These common characteristics are discussed here, rather than repeated for the individual systems.

b. Advantages and Disadvantages of the Slagging Concept

*(1) Advantages. Residue volume reduction* – The maximum possible refuse volume reduction (about 97.5%) can be achieved through slagging of the residue. This is equivalent to reducing one ton of refuse with a volume of 154 cubic feet (assumed density of 350 lb/cu yd), to a residual volume of only 3.78 cubic feet (at 110 lb/cu ft). Conventional incineration results in volume reductions of 50 to 80%.

*Residue quality* – All putrescible matter is destroyed in producing the slag. Solidifying the slag can be performed rapidly in a quench tank, or more slowly after separation of the metal and slag phases. Rapid quenching in water produces porous, coarse granules. Ferrous metals can be removed magnetically from the quench tank. The residue is suitable as a fill material. Slow cooling is a convenient, less expensive process and may enable production of a stronger, more useful and valuable aggregate material.

*Flue gas odors* – All odor-causing organic species will be completely consumed in processes involving uniform combustion gas temperatures over 2000°F in the presence of excess oxygen or air.

*Flue gas volume* – Most of the processes utilize less combusion air than conventional furnaces where large amounts of excess air are needed to control refractory fluxing and to minimize fly-ash adherence. Thus, per pound of refuse burned, the weight of gas passed to the flue gas conditioning system is less for most slagging incinerators. If the gases are cooled to the same temperature prior to entering the air pollution control device, the capacity (cost) of the control device would be proportional to the flue gas volume; this suggests that smaller control devices could be used for slagging units. However, in the case of slagging incinerators, the gas cooling system must process a larger heat load and perhaps a higher inlet volumetric flow rate, depending on temperature and excess air levels, thus partially offsetting savings in APC system capital and operating costs. Part of this heat load may be removed in a waste heat boiler or exchanged as preheat for the combustion air, reducing the supplementary heat requirement for the process.

*Elimination of grates* – Although some of the systems do not require grates for supporting the refuse while it is burning, other components, such as the water-cooled monkey and monkey cooler, refractories, and water-cooled walls are exposed to high temperature fluxing and oxidation-corrosion, which may offset the advantages from elimination of grates.

*(2) Disadvantages. Air pollution* – The higher temperatures required for slagging may result in substantially more nitrogen oxide formation than is generated in normal incineration. For combustion gases at 10% excess air, the equilibrium nitric oxide concentration rises from 200 ppm at 2000°F to 2000 ppm at 3000°F. Although equilibrium concentrations may not be reached due to kinetic limitations, the rate at which the equilibrium concentration is approached increases rapidly with temperature. As discussed in Chapter V, the total nitrogen oxide generation rate (lb/hr) from incineration appears to correlate with the heat release rate (Btu/hr) as it does in the combustion of fossil fuels. The higher gas temperature attained in slagging incinerators would lead to expectation of higher rates of nitrogen oxide formation.

Other inorganic gaseous pollutants derived from the combustion of refuse will be unchanged from the amounts generated in normal incineration operations at 1800°F. Particulate emissions and the efficiency of necessary emission control will vary with the design of the systems. Those systems characterized by high gas velocities, which tend to entrain particulate, may require more efficient particulate removal devices to reach the same emission level as conventional incinerators.

*Auxiliary heat requirement* – Supplementary heat required to maintain slagging temperatures will result in a significant additional operating cost above that of conventional incineration.

*Operational complexity* – The addition of ash fusion to the incineration process complicates operation. If slagging and incineration are performed in the same unit (Type I), difficulties with ash fusion and slag tapping will affect the incineration portion of the process. If the slagging is performed in a separate unit (Type II), the two operations must be kept somewhat in phase to prevent buildup or depletion of residue inventory. In either type of slagging operation, the startup process will be more difficult than in conventional systems; this would be of particular concern if the system were shut down daily.

*Safety* – The higher temperatures and operations needed in the molten material process make slagging systems inherently more hazardous than conventional systems. However, handling of such materials, on much larger scales, is done routinely in many industries.

*Operational sensitivity* – Slagging processes depend upon maintaining temperatures in a range bounded on the low side by slag fluidity requirements and on the high side by the limitations imposed by the design and materials of construction. Although the upper limit may be reasonably well defined, the lower limit is strongly related to residue composition. Variability in refuse heat content or residue characteristics could, therefore, demand frequent changes in operating conditions (or feed rates of fluxing additives). If auxiliary fuel is used, an alert operator is necessary to minimize fuel use (operating cost). In view of the large number of plants now being operated under unfavorable combustion conditions (due to operator inattention to combustion air adjustment), it is clear that greater efforts in employee motivation or rewards may be needed to avoid high operating costs or frequent malperformance of the plants.

### c. Problem Areas Inherent in the Slagging Concept

*(1) Operating labor* – Because of the relatively complex nature of these processes, greater operating labor skills will be required than in conventional incinerator operations. This requirement will necessitate additional employee training; may result in higher labor costs; and should place increased emphasis on employee retention efforts.

*(2) Design and materials of construction* – The high temperatures and operational sensitivity of slagging systems require a highly-engineered, integrated design, with special care in the selection of materials; and a high level of process equipment and instrumentation maintenance to ensure acceptable unit life and reliability. The effects of thermal cycling, if the unit is shut down daily, may be more severe in high-temperature systems.

*(3) Slag fluidity* – Difficulties may be encountered with poor slag fluidity (high viscosity) and solidification due to either poor temperature control or variations in the noncombustible content of the refuse. Depending upon the properties of the noncombustibles, varying amounts of limestone or other fluxing agents may be required.

### d. Process Economics

*(1) Capital Investment.* Slagging systems contain components which are common to conventional incineration plants:

- foundations, buildings, shops, locker rooms, and offices;
- refuse storage and handling equipment;
- furnace;
- flue gas conditioning system;

- air pollution control system;
- residue handling equipment; and
- induced draft fan and stack.

The costs for the first two components are expected to be the same as for conventional systems: comprising about 40-60% of the total capital investment. Slagging system furnaces will be required to withstand higher temperatures; however, grate systems are eliminated, except in those systems where a slagging furnace is added after conventional incineration. The furnace portion of plant investment for most slagging systems would thus be expected to fall within a 20% range of conventional continuous grate system costs. For conventional plants, this part of the system makes up 35-45% of the total capital investment. Specific system configuration will be treated in more detail later.

The air pollution control devices, flue gas conditioning systems, fans and stack generally comprise 8-12% of the total capital investment of conventional systems, depending upon the type of control used and the flue gas volume. If the same particulate loading and removal efficiency are required, the savings in the cost of APC equipment is roughly proportional to the ratio of total volumetric flue gas rates raised to the 0.7 power for precipitators and to the 0.8 power for other devices. The cost for additional gas cooling capacity would tend to offset some of this saving. A maximum savings of about 5% of the total capital investment may thus be possible for slagging systems.

Residue handling equipment generally comprises only a few percent of the total conventional plant investment. The significantly lower ash volume would result in savings of 50-75% of the cost of this rather minor part of the total system. These savings could be offset by the cost of slag and metal cooling systems, particularly if slow cooling or any special processing is attempted.

In summary, investment costs for slagging incinerator systems should not vary significantly beyond the normal spread in costs for conventional grate systems. Savings in residue handling and air pollution control equipment may well be offset by increased system costs associated with the slagging aspect of the furnace.

*(2) Operating Costs.* Operating costs for slagging incinerators are discussed in relation to costs for conventional, continuous incinerators developed earlier in this report. Particular system costs are treated more specifically in sections to follow.

*(a) Variable Costs.* By far, the most significant cost difference between slagging and conventional incinerators is the supplementary energy input required to maintain slagging temperatures. As discussed earlier, the amount of energy required depends upon system design, refuse composition, and the form of the energy input. For systems adequately described in Figure VII-34, refuse containing 28% moisture burned with 25% excess air requires a supplementary energy input of 1.5 MM Btu/ton of refuse burned. As an example, if energy is provided by charging coke ($20.00/ton; 12,000 Btu/lb) with the refuse, the slagging fuel cost is $1.25/ton refuse (16 tons refuse/ton coke). Reduction in this cost is possible by use of other, cheaper fuels, such as gas at about 50¢/MM Btu (75¢/ton of refuse). If energy recuperation is used to preheat the combustion air to reduce or eliminate the external supplementary heat requirement, any operating cost savings would be partially offset by an increase in the capital investment required.

Electric power costs should be about the same as for normal incinerators. For cooling of combustion gases, at 25% excess air, from 3000°F to 600°F, approximately 25% more water is required than is used in conventional incinerators in cooling gases at 100% excess air from 1800°F to 600°F. At 30¢/M gal. this is equivalent to a maximum additional water cost of about 7¢/ton. Overall, there would only be minor differences in utility costs for slagging systems relative to conventional systems.

*(b) Semi-Variable Costs.* No significant differences are anticipated in operating labor relative to conventional systems. Any savings in residue handling manpower would be offset by an operator tending the slagging end of the system or handling fuel or limestone for processes involving their use.

The high temperatures of slagging systems would result in higher refractory maintenance costs than incurred in conventional systems. Instrumentation and control system maintenance would also be increased. However, elimination of grate maintenance or reduced grate area per ton processed may compensate for the higher refractory maintenance and result in a slightly lower overall cost for slagging incinerators.

*(c) Fixed Costs.* Since fixed costs vary directly with the capital investment, it is expected that these costs will be similar to those for conventional systems.

*(d) Other Economic Considerations*

- *Metal Salvage* – If the average metal content of refuse is estimated at 8%, a maximum of 160 pounds of metal could be salvaged per ton of refuse. However, some fraction of this would be oxidized in the incineration process. The ferrous metal can be recovered magnetically in the form of pellets, from water-quenched slag, or solidified after separation from the nonmetal slag phase. The current price of scrap iron varies regionally from $15-30/ton, offering a maximum credit of $0.87 to $1.75/ton of refuse for the slagging process. The capital investment for such recovery equipment should be small. However, this metal has yet to be proved valuable in the recovered form or as feed for steel-making. For use as a steel-making feed, the maximum copper content of scrap is 0.3% by weight; for foundry applications, tolerable limits are higher for some applications with foundries representing a much smaller scrap market than the steel industry. (See also Appendix F.)

The copper content of the metallic phase material in the Melt-Zit[70] and Ferro-Tech[73] slagging incinerator tests was reported to range between 0.03 and 0.3 weight-percent. This raised some question of the desirability and potential value of this material since several of the analyses were so close to the tolerable limit. Certainly the demand and price for the metal will reflect the local market; however, it would be difficult to project a price exceeding $5-10/ton of metal (at the incinerator), if a market can be found at all, until user confidence is developed in the reliability of the composition of this material.

It is interesting to note here that zinc is not tolerable in scrap used for steel-making because the formation of liquid eutectic mixtures of zinc oxide with refractory constituents tends to deteriorate the furnace refractory. Although not present in the magnetic material in the Melt-Zit tests, the slag phase contained about 0.25 weight-percent zinc oxide, perhaps contributing to the refractory deterioration observed in the tests.

- *Solidified Ash* – The nonmetallic phase of the slag has potential use as an aggregate for low-strength concrete blocks. In the tests referred to above in which both phases were quenched in water, Kaiser found the nonmetal portion of the solid to be friable, readily crushed underfoot, and not comparable in strength to sand or stone as used in concrete or road building.[70] A stronger aggregate may possibly be produced by slower cooling of the slag, rather than by quenching. Again, the commercial value of the material has yet to be demonstrated and would vary with local markets.

- *Residue Disposal Operations* – The absence of putrescible material and the decreased volume of residue should reduce the cost and land area requirements for disposal operations. It is also likely that land reuse may be more rapid than in the case of untreated refuse landfills. The material may also be used as a fill for road and construction applications near the incinerator.

### e. Specific Slagging Process Concepts

In this section, specific systems involving slagging of incinerator residue are described relative to the general discussion of slagging incinerators just covered. The processes vary in form of energy input to maintain the slagging temperature and in the sequence of refuse combustion and slagging steps. In the first two processes described (Melt-Zit and Torrax) slagging and incineration occur in the same chamber (Type I slagging systems). In the remaining processes, slagging occurs in an essentially separate operation (Type II slagging systems).

#### *(1) Melt-Zit High-Temperature Incinerator – American Thermogen Division, Process Plants Corporation*

#### *(a) Process Description*

The primary furnace used in Melt-Zit process is a vertical shaft furnace operating between 2800°-3500°F. In this furnace, the combustibles are incinerated and the metals and other inerts are converted to a molten slag which flows from the base of the unit into a quench tank. Slagging occurs in the refuse bed which rests on a bed of high-temperature coke at the bottom of the shaft furnace. The system includes two unique components; viz., a feeder for coke and limestone as required for the slag fluidity and a vertical shaft furnace and secondary combustion chamber.

The shaft furnace is shown in Figure VII-35 and a proposed flue gas conditioning and cleaning system in Figure VII-36. The refuse burns partly in suspension in the shaft and partly on the surface of the coke bed. Slag and metals are drained through a tap hole at the bottom of the coke bed. Burnout of combustibles carried over in the combustion gases occurs in the secondary combustion zone.

A pilot-scale system for development and demonstration purposes was built in Whitman, Massachusetts, by the American Design and Development Corporation, the developers of the process. (They have since become the Thermogen Division of Process Plants Corporation.) The pilot unit has a 3- to 5-foot diameter furnace which is 48 feet high. The shaft furnace portion of the incinerator was tested in March 1968 under a program sponsored jointly by the Department of Health, Education and Welfare, Bureau of Solid Waste Management, and the city of Brockton, Massachusetts.[70] Based on the report findings, the system operated poorly and proved unreliable. However, the poor performance may be attributable, in large part, to the fact that only the vertical shaft furnace was tested, after having been physically disconnected from the secondary combustion chamber and gas conditioning portions of the system. Operating the system in this manner resulted in loss of control of its combustion air needed for the process. This condition may have contributed both to the high solids carryover and high coke consumption as well as to the slag temperature and drainage problems.

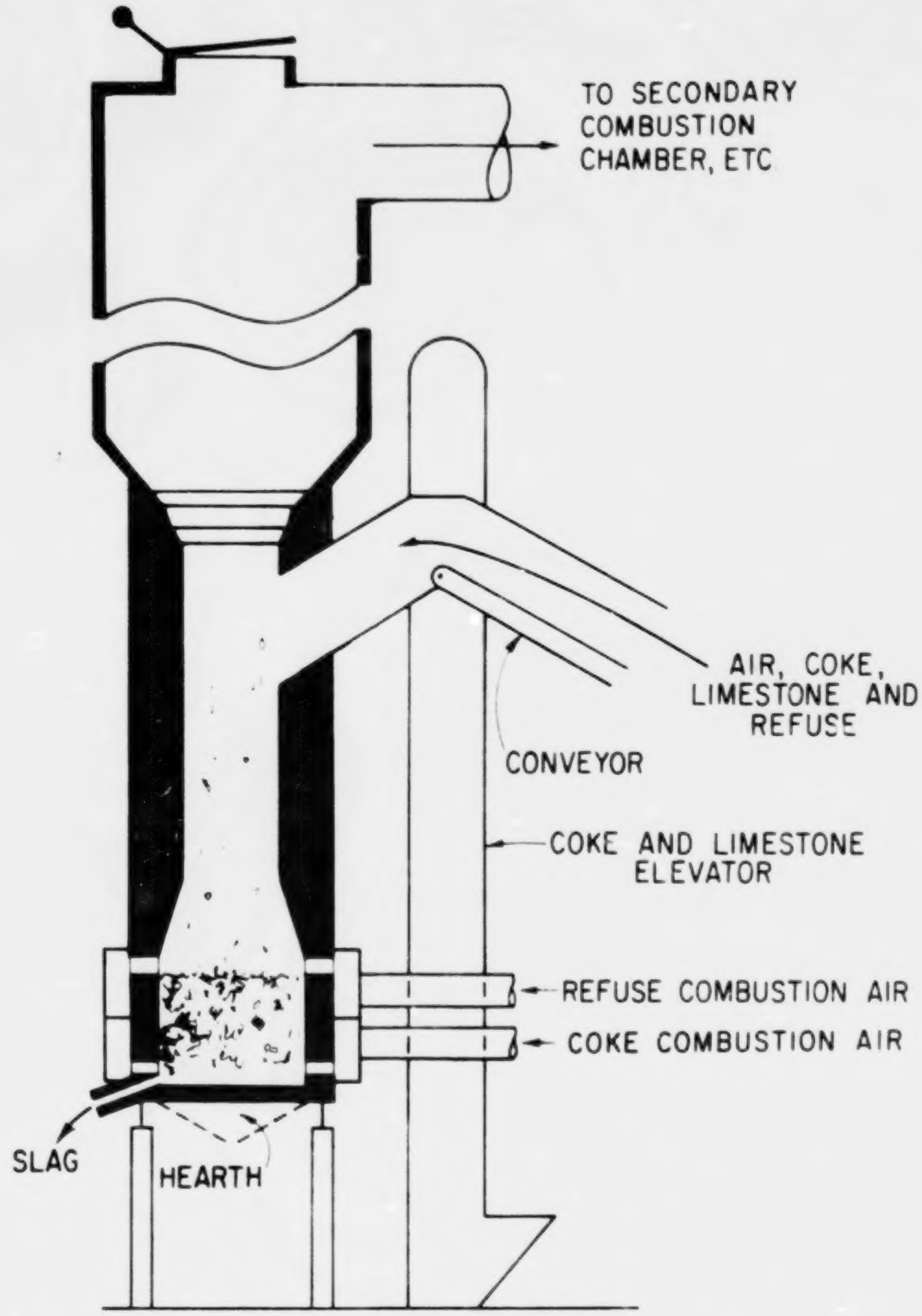

TO SECONDARY COMBUSTION CHAMBER, ETC
AIR, COKE, LIMESTONE AND REFUSE
CONVEYOR
COKE AND LIMESTONE ELEVATOR
REFUSE COMBUSTION AIR
COKE COMBUSTION AIR
SLAG
HEARTH

FIGURE VII–35 AMERICAN THERMOGEN SYSTEM

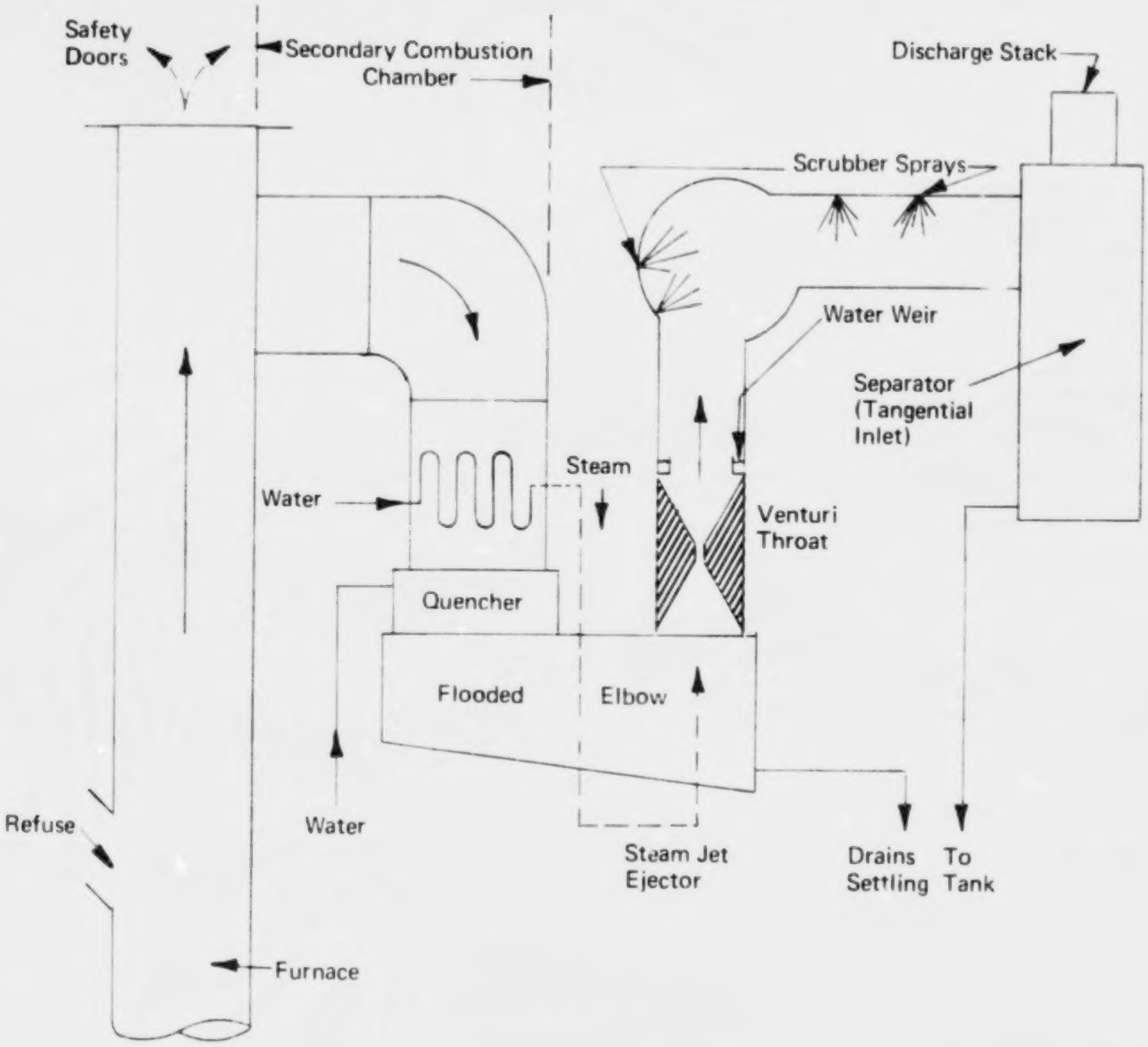

Safety Doors
Secondary Combustion Chamber
Discharge Stack
Scrubber Sprays
Water Weir
Separator (Tangential Inlet)
Steam
Water
Venturi Throat
Quencher
Flooded
Elbow
Refuse
Water
Steam Jet Ejector
Drains Settling
To Tank
Furnace

FIGURE VII–36 PROPOSED HOT-GAS FLUE AND GAS SCRUBBER FOR AMERICAN THERMOGEN SYSTEM

Under these unfavorable conditions, system performance was characterized as follows:

- *Low Refuse Firing Rate* – A maximum firing rate of 1.6 TPHr was achieved during the test period. This rate could probably not be exceeded by more than 25% to 30% without excessive solids entrainment in the flue gas.

- *High Coke Consumption* – Due to poor air control to the coke bed, coke consumption rates varied from about six to eight tons of refuse per ton of coke.

- *Poor Slag Drainage* – Failure to reach adequate temperatures contributed to high slag viscosity. During the periods of good slag drainage, slag temperature ranged between 2530 and 2650°F. To increase slag fluidity, limestone (1 ton per 36 tons of refuse) and fluorspar (7 pounds per ton of refuse) were added. There was, however, incomplete slag fluxing.

- *High Fly Ash Loading* – About 10% of the weight of the refuse charged was carried over with the flue gases, including unburned material, partially pyrolized combustibles and ash material. This value is about 10 times higher than the average value for more conventional systems (as discussed in Chapter VI). If corrections are made, however, for the higher ash and moisture content of the refuse used, and if it is assumed that combustible particulates would be burned out to the same level as for existing units, the emission drops to about three times the "normal" or 66 lb/ton. A significant fraction of the ash (about 25%) is, however, carried over with the flue gas and is not slagged unless it can be reintroduced into the furnace without re-entrainment in the gas phase.

- *Refractory Lining Degradation* – The refractory lining at the lower part of the coke bed deteriorated due to the fluxing action of slag constituents at the high temperature.

The refuse burning rate was found to be limited by the rate of melting of the inerts and by the rate of carryover of the solids by the gas. A secondary combustion chamber (not used in the test) is necessary for completion of combustion of entrained solids and gases. This lack somewhat biased the test results. Operation of the complete system should improve the control of combustion air, permitting more complete combustion with a lower level of solid carryover and coke consumption. Based upon test results, the capacity of a 7-foot throat diameter commercial unit would be about 210 TPD, with possible increase in capacity of up to 30%. This capacity would be limited primarily by the solids loading in the combustion gas.

*(b) Advantages and Disadvantages*

The system advantages are similar to those given in the general slagging incinerator discussion, but include the elimination of metal grates.

System disadvantages, in addition to those listed in the general presentation, include the following:

- The auxiliary heat requirement, which is furnished by coke combustion, is relatively expensive. However, the coke also serves as a support grid for the slagging of inerts.
- Relative to conventional systems, the Melt-Zit process has a high degree of operational complexity and sensitivity, as reflected in the effect of air rate control on solids carryover, coke consumption, slag temperature, and fluidity. Difficulties with slag fluidity can interfere with operation of the entire process.
- Particulate emission control may be more difficult for this type of furnace because of the tendency of solids to carry over in a vertical shaft furnace, particularly when solids are fed counter-current to the gas stream. This is especially true for bits of paper and metal foil.
- Nitrogen oxide emissions may be higher than in conventional systems, as a consequence of the higher temperature of combustion in the coke bed. This problem may be reduced, however, if the coke bed can be operated at or below stoichiometric conditions.

*(c) Problem Areas*

As indicated by the demonstration unit tests results, the following problems require further design and development considerations:

- *Carryover of Solids* – Air control and burnout of suspended combustibles in a secondary combustion chamber are necessary to reduce furnace emissions below that measured in the test program. The flue gas flow rate also influences the refuse burning capacity of the system per unit cross-sectional area of the furnace, in that the maximum tolerable air rate also corresponds to the maximum refuse burning capacity for a given size furnace. Improved air control may permit higher throughput.

- *Slag Fluidity and Drainage* – Proper air and temperature control should minimize slag fluidity and drainage problems and may reduce limestone flux consumption.

- *Refractory Deterioration* – Chemical and thermal deterioration of the refractory in the slagging zone will represent a continuing maintenance problem, unless more efficacious system designs and construction materials are used to minimize the refractory wastage.

*(d) Economics*

The general investment economics discussed for slagging incinerator systems also apply here. Although the system is comparatively simple in design, the solids carryover must be reduced to minimize the efficiency requirement of the air pollution control equipment.

Coke consumption rates measured during the tests (0.12 and 0.17 ton per ton of refuse) correspond to operating costs of $2.50 to 3.32 per ton of refuse for supplementary fuel. During the period that these coke consumption rates were measured, the unit was burning refuse containing 38% moisture at about 25% excess air (considering both coke and refuse combustion air). At these conditions, Figure VII-34 indicates a supplementary heat requirement of about 2.5 MM Btu/ton of refuse. The measured coke consumption rates correspond to heat inputs of 3.1 and 4.1 MM Btu/ton refuse. Figure VII-34, however, was developed on the assumption that all combustion products would be brought to slagging temperatures. In this case, only part of the combustion gases has to reach these temperatures. On the assumption that the resulting *mixed* gas stream would be in the temperature range of 2000-2500°F, rather than at 3000°F, a supplementary heat requirement of less than 2.5 MM Btu/ton refuse would be necessary. For a lower moisture content refuse, say 28%, heat inputs of about 1 to 1.5 MM Btu/ton would be expected, corresponding to coke costs of $0.80 to 1.20/ton of refuse.

Limestone at a rate of 0.026 ton/ton of refuse was used as a flux to increase slag fluidity. At a cost of $6.00/ton, this consumption rate corresponds to an operating cost of about $0.16/ton refuse. For a refuse ash content of about 22%, the limestone would increase the residue weight about 10%. This would have a negligible effect on the overall volume reduction of the process. Limestone may not be required if coke use can be discontinued.

If fluorspar is necessary in commercial operation, its cost would be about $0.02 per pound used. During the tests, about 7 pounds per ton of refuse were used. This represented an incremental expense of about $0.14/ton refuse. With proper air and temperature control, the slag fluidity problem could be decreased, reducing or eliminating the need for flourspar.

### e. *Future Research*

American Thermogen has initiated research into the use of natural gas instead of coke as the source of supplemental heat energy. They feel that better thermal efficiency and reduced (or eliminated) limestone use will be obtained with gas firing. Tests are expected to begin in early 1970.

### *(2) The Torrax Solid-Waste Disposal System – Torrax Systems, Inc.*

### *(a) Process Description*

The primary incineration chamber of the Torrax System is a vertical shaft furnace in which refuse is loaded from the top. Pyrolysis and partial combustion, assisted by preheated air injection, occur at the base of the furnace. Inert material is melted at a temperature of about 3000°F. The pyrolysis and combustion products then pass to a secondary combustion chamber (the "igniter") where additional air is introduced to complete the combustion reactions. The entire system is schematically shown in Figure VII-37.

In addition to the usual structures and refuse and residue handling equipment, the system as proposed by Torrax Systems, Inc., consists of the following major components:

- hot blast heater – a gas-fired heat exchanger with silicon carbide tubes and internals;
- gasifier or vertical furnace – the combustion and pyrolysis furnace where noncombustibles are slagged;
- igniter – a secondary combustion chamber;
- cooling tower – a water spray tower for cooling of the gases prior to particulate collection in a control device; a waste heat boiler could be utilized;
- particulate emission control device – fabric bag filter.

Air is fed to the primary furnace combustion chamber by a blower; it then flows inside the silicon carbide tubes of the hot blast heater. The same blower provides combustion air for the natural gas fuel used to fire the heater, external to the silicon carbide tubes. The air is preheated to about 2000°F and flows to the furnace in refractory-lined ducts.

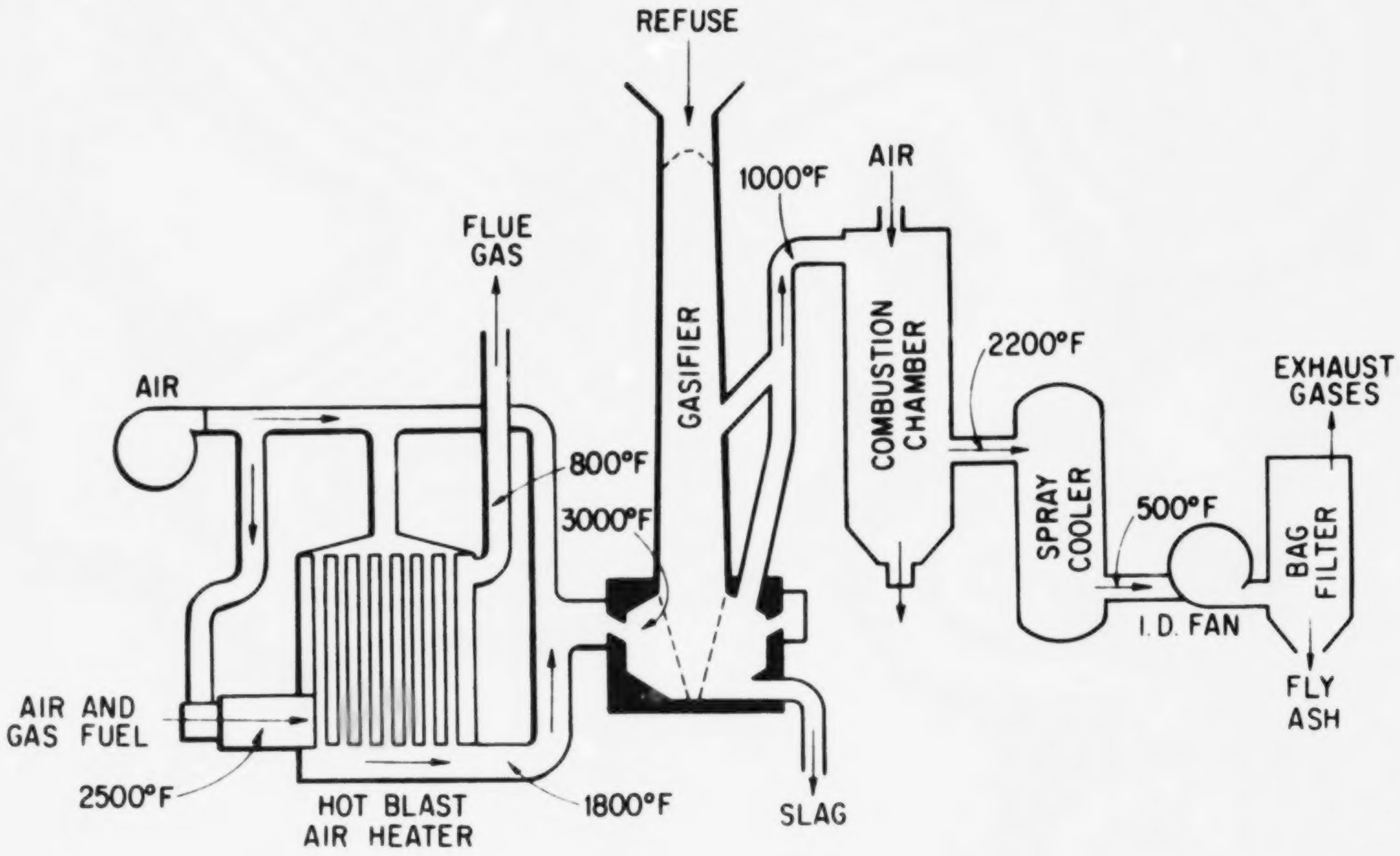

REFUSE
GASIFIER
1000°F
AIR
FLUE GAS
COMBUSTION CHAMBER
2200°F
EXHAUST GASES
AIR
800°F
3000°F
SPRAY COOLER
500°F
BAG FILTER
I.D. FAN
FLY ASH
AIR AND GAS FUEL
2500°F
HOT BLAST AIR HEATER
1800°F
SLAG

FIGURE VII–37 TORRAX SYSTEM

A refuse level is maintained at the top of the vertical furnace, the refuse dropping by gravity as it is consumed. The primary purpose of this unit is to generate carbon monoxide and pyrolysis gases by means of the thermal decomposition of organic matter in the refuse. Noncombustibles and large, slow-burning articles reach the bottom of the furnace. Combustion is completed and inert material is melted in this high-temperature (~ 3000°F) section of the gasifier.

The gases from the gasifier pass to the secondary combustion chamber (igniter) where secondary air is admitted and combustion is completed. Exhaust gases are discharged from the igniter at about 2200°F, and are then cooled in a spray tower to about 500°F before passing to a baghouse, chosen for particulate control for this process.

No combustion air is required in the gasifier for the externally fired supplementary fuel and the air for combustion of refuse is, by design, below stoichiometric. Solids carryover into the secondary combustion chamber falls in proportion to the gas velocity in the gasifier. Since solids carryover is one of the limiting factors in determining the refuse-burning capacity of a given furnace, at the lower air rates and lower flue gas velocities characteristic of the Torrax concept, higher capacities per unit cross-sectional area are possible than in units requiring all refuse and auxiliary fuel combustion air to be added in the primary combustion furnace. Slagging temperatures should be maintained in the igniter with minimum carryover of fly ash into the spray tower in order to meet the objectives of a slagging process; viz., slagging the major part of the inerts while maintaining a reasonable load on particulate control devices. No data are available, however, to evaluate these parameters.

Torrax Systems, Inc., is a joint venture of the A.E. Anderson Construction Corporation of Buffalo, New York, and the Carborundum Company of Niagara Falls, New York. The system is described in a recent Torrax brochure.[71] Plans to build a 75-TPD pilot demonstration plant in Erie County, New York,[72] have recently been announced. The plant construction and testing will be jointly sponsored by a federal grant, state and local government contributions; and contributions from the American Gas Association.

*(b) Advantages and Disadvantages*

The unique system advantages of the Torrax unit include:

- elimination of grates;
- external supply of supplemental energy, using natural gas, a relatively cheap source of energy compared to other systems which use either coke, electricity, or oxygen enrichment to maintain slagging.

The following disadvantages, in addition to those listed in the general presentation, apply to the Torrax system:

- greater operational complexity and sensitivity than most other slagging systems (see Melt-Zit);
- despite attempts to minimize particulate carryover, it is likely that the particulate furnace emissions will be higher than in conventional continuous-feed systems.

*(c) Problem Areas*

Since the system has yet to be built and tested, potential problem areas can only be hypothesized at this point. They include:

- Slag fluidity may represent a problem, especially in the igniter section where exhaust gases are known to reach a temperature of only 2200°F.
- Solids loading may be high, and deterioration of the refractory may result where it contacts the slag.
- Unless the igniter is especially designed for long retention times and excellent mixing characteristics, the combustible pollutant emissions could be significantly higher than in conventional systems.

*(d) Economics*

The Torrax system is more complex than systems which are directly fired for supply of required supplemental energy. The capital costs for the furnace and hot blast heater in the Torrax system will probably be higher than those for the less complex systems, but the system offers a possible lower level of solids carryover. Costs are still expected to be within the range of conventional incinerator systems, especially when one considers the overall costs of the complete system, including buildings and materials handling equipment. An excess air level of 15% represents a potential reduction in APC investment of about 40% to 50% relative to a process operating at 200% excess air, for the same collection efficiency and inlet solids loadings. A higher solids loading relative to conventional incinerator systems, however, would require a higher collection efficiency, perhaps offsetting savings due to capacity. Also, it may be difficult to obtain efficient burnout of combustibles in the igniter with such low levels of excess air. The potential savings in APC capacity will be eroded as excess air is increased.

Although Torrax has not projected capital or operating estimates for the system, the American Gas Association[72] has announced that the unit will use about $0.75 worth of gas for each ton of refuse consumed. At gas costs of from $0.40-0.50 MM Btu's, this corresponds to a supplementary energy input of from 1.5 to 2.0 MM Btu/ton of refuse. This system is expected to operate at excess air levels as low as 15%, but the actual level must be determined in tests. The supplementary energy requirements indicated in Figure VII-34 are in the same range as those anticipated for the Torrax system, although the gases do not leave the gasifier at 3000°F in the Torrax system. However, since the supplemental energy is supplied through a gas-to-gas heat exchanger, only about two-thirds of the energy in the gas is used in the furnace system. The net energy requirement agrees with that predicted for the generalized system in Figure VII-34.

The pressure drop across the Torrax system may be high, requiring a high power level for the combustion air blowers and the induced draft fan. Consequently, power requirements may be high relative to conventional systems, which involve power costs of about $0.15/ton of refuse for fan power (at 1.5 inch of water pressure drop, exclusive of air pollution control equipment).

The use of limestone or other fluxing agents has not been discussed in descriptions of the system operation. Experience in the pilot facility will determine whether limestone is needed for fluxing at the temperatures achieved in the base of the vertical furnace.

### *(3) Slagging Incineration Using Oxygen-Enriched Air*

#### *(a) Process Description*

An alternative to supplementing refuse heat content to maintain slagging temperatures, as suggested in Figure VII-34, is to reduce the sensible heat content of the flue gas stream at the slagging temperature. This can be achieved by oxygen enrichment of the combustion air to reduce the weight of flue gas per pound of refuse burned. In principle, this is similar to reduction in excess air level, but the availability of sufficient oxygen for complete combustion is assured. Although no specific systems have been tested utilizing oxygen-enriched air for slagging incineration, the concept would be used most advantageously to promote slagging in processes which involve combined incineration and slagging of residue in a single combustion chamber with no grate system. A schematic of such a unit is shown in Figure VII-38.

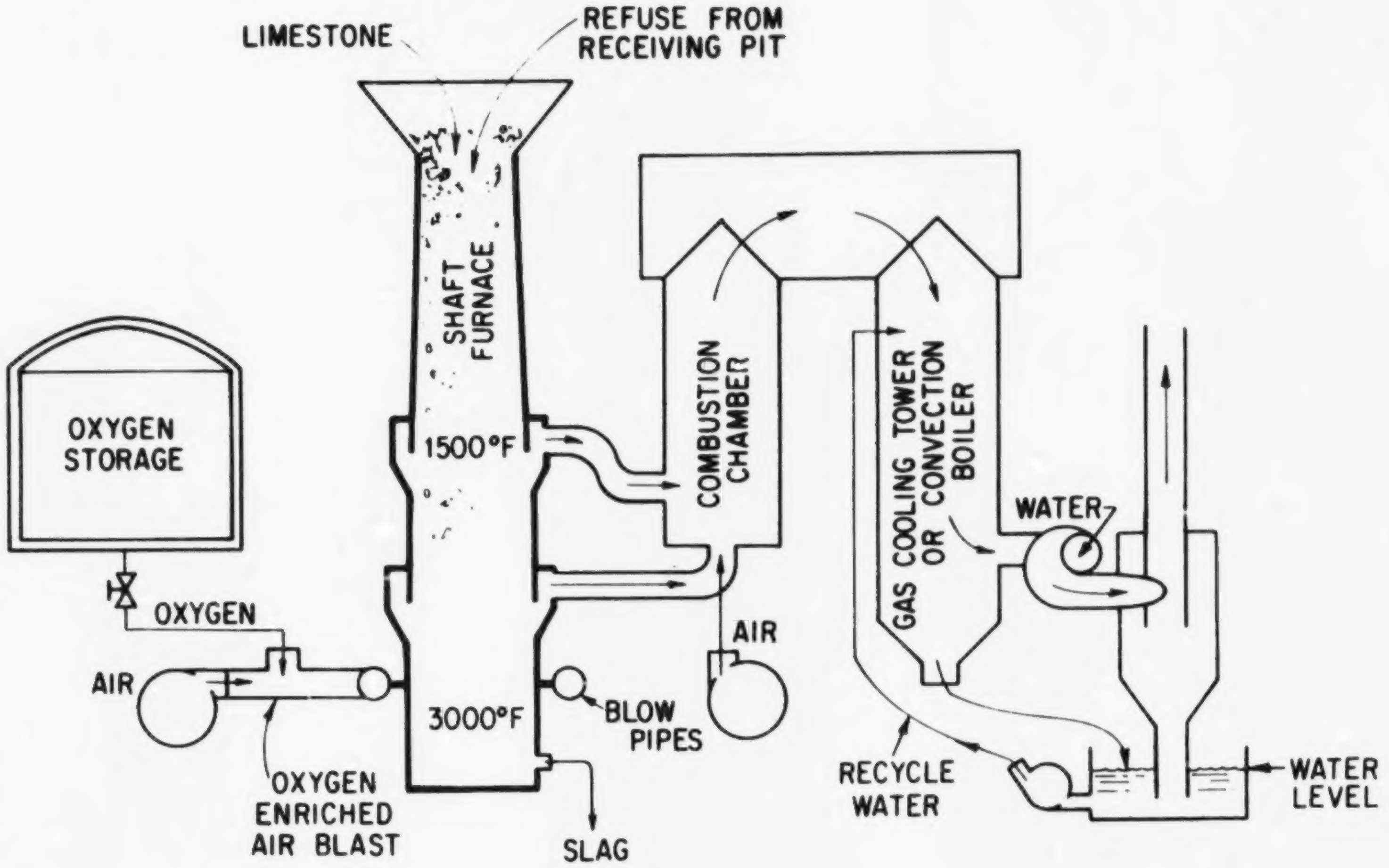

LIMESTONE
REFUSE FROM RECEIVING PIT
SHAFT FURNACE
1500°F
3000°F
OXYGEN STORAGE
OXYGEN
AIR
OXYGEN ENRICHED AIR BLAST
BLOW PIPES
SLAG
COMBUSTION CHAMBER
AIR
GAS COOLING TOWER OR CONVECTION BOILER
WATER
RECYCLE WATER
WATER LEVEL

FIGURE VII–38 OXYGEN ENRICHMENT SYSTEM

The assumptions and energy balance for the idealized system used in developing Figure VII-34 were used to estimate the enrichment levels required to maintain a furnace temperature of 3000°F without the addition of supplemental energy:

- For refuse containing 28% moisture and 22% noncombustible material, burned with a 25% excess of enriched air, air enrichment to 27 volume percent oxygen is required. The enriched air would be produced by blending gaseous oxygen with air at a rate of 0.094 lb of $O_2$ per lb of enriched air. This is equivalent to an oxygen use of 0.28 ton per ton of refuse. The weight of combustion gases would be reduced by about 25% from the level resulting from conventional incineration using air at the same excess air level.

- For refuse containing 38% moisture and 20% noncombustibles burned at 25% excess enriched air, enrichment to about 36 volume percent oxygen would be required to maintain slagging temperatures. The oxygen requirement would be 0.22 lb per lb of enriched air, or 0.41 ton per ton of refuse consumed. A 43% reduction in the weight of flue gas generated is achieved relative to the use of normal air at the 25% excess level.

The oxygen requirements given above, similar to the supplemental energy requirements in Figure VII-34, are for the idealized case discussed in the general technology section. Actual oxygen enrichment levels, as the supplemental energy requirements, are subject to variations due to actual design and performance of the real system. Of primary importance is the realization of good gas phase mixing to take maximum advantage of the available oxygen. However, the supplemental energy requirements of Figure VII-34 were good approximations to the energy requirements of real systems. Similar results would be expected for the oxygen requirements.

Oxygen required for enrichment of combustion air would probably be purchased rather than produced at the incinerator facility. At an average refuse moisture content of 28%, oxygen usage would range from 14 TPD for a 50-TPD incinerator to 84 TPD of oxygen for a 300-TPD incinerator (assuming 24-hour operation at full capacity). Oxygen requirements of up to 120 TPD would exist for 300-TPD incinerators burning 38% moisture refuse. Twenty-five TPD of oxygen use corresponds to about the smallest requirement which would justify construction of an oxygen plant near the incinerator under long-term contract for supply of the oxygen. Such an air-separation plant would be owned and operated, typically by the supplier under a long-term contract with the incinerator operator. For smaller users, an on-site oxygen storage tank, filled on a regular basis by the oxygen supplier, would be used.

*(b) Advantages and Disadvantages*

Although no specific system design has been proposed, the essential advantages, disadvantages, and important economic implications of using oxygen-enriched air for slagging incineration can be examined. In addition to the comments made in the general presentation, the comments that follow are unique to the oxygen-enrichment concept.

Advantages would be realized (a) through a reduction in the amount of combustion gases per unit of refuse consumed; (b) increasing the capacity of a shaft-type furnace per unit cross-sectional area; or, (c) at the same capacity per unit cross-sectional area, reducing the gas velocities, thereby reducing the expected amount of particulate carryover. The reduction in gas throughput would be reflected in smaller capacity particulate control devices relative to conventional systems. However, depending upon actual system design, the solids loading level may be higher, requiring higher collection efficiencies; this would offset any saving due to the smaller volumetric throughput. In addition, since no supplemental energy is added to the process to maintain slagging temperatures, there is no additional heat load on any gas cooling that is performed prior to particulate removal.

The principal disadvantage of enrichment is the high cost of oxygen as an alternative to combustion of a fuel to maintain slagging temperatures. The higher concentration of the oxygen would also result in the formation of a somewhat higher amount of nitrogen oxides than in slagging systems in which air is used at the same temperature levels. In addition, operational complexity and sensitivity of process operation and control to the oxygen enrichment would be expected. The enrichment level would have to be adjusted for changes in refuse moisture to maintain furnace slagging temperatures.

*(c) Problem Areas*

The potential problem areas common to the slagging systems already discussed are appropriate to this process concept. In addition, however, the lower volume of combustion air would tend to reduce the amount of mixing relative to combustion with normal air; this could affect the combustion efficiency. Also, plant operational reliability could be dependent upon the oxygen supplier and on the operation of the oxygen storage and metering systems. Some safety problems would also be encountered in use of oxygen, in both the oxygen handling systems and the incinerator heat release rates.

*(d) Economics*

Purchased oxygen costs vary from about $29 per ton of oxygen used at the rate of 15 TPD, to $15 per ton at 100 TPD. Thus, at the most advantageous prices, oxygen costs would exceed $4 per ton of 28% moisture refuse and $6 per ton of 38% moisture refuse. The investment credits which may be obtained from the use of the enriched air and the resulting lower gas volumes would make up for only a very small fraction of this high operating cost increment.

### *(4) Ferro-Tech Total Incinerator – Ferro-Tech Industries, Inc.*

### *(a) Process Description*

The Ferro-Tech Industries system involves conventional incineration of refuse on a grate, followed by discharge of the residue directly into a coke-fired melting furnace. This system is designed as an integrated unit. The primary furnace combustion gases are used to preheat the melting furnace combustion gases. This system, as proposed by Ferro-Tech Industries of Pittsburgh, Pennsylvania,[73] is shown schematically in Figure VII-39. The unique components of this system are the coke-fired melting furnace and the air preheating system which provides combustion air to the melting furnace.

In operation, combustion of approximately 90% of the combustible material in the refuse occurs on the primary combustion chamber grate system. Incompletely combusted, slow-burning material and noncombustible residue are discharged from the end of the grate and fall into the coke-fired melting furnace. The air serviced to the melting furnace is preheated by heat exchange with the gases leaving the primary furnace. Here combustion is completed and the ash and metals are fused. The slag is tapped from the bottom of the melting furnace and the slag and metal phases are separated by decantation prior to solidification. The melting furnace walls are water-cooled to reduce refractory deterioration. The melting furnace is designed for low gas velocities through the coke bed to allow for slag drainage through the bed and to minimize fly ash suspension. Combustion of unburned species in the flue gas from the primary and melting furnaces occurs in the secondary combustion chamber; gases are then scrubbed for particulate removal.

Ferro-Tech Industries has conducted a pilot study of the basic slagging concept using a 36-inch diameter, water-cooled, iron-melting cupola. The tests were conducted in May 1969 to demonstrate the feasibility of incineration and slagging in a cupola, but they did not involve testing of the overall Ferro-Tech system shown in Figure VII-39. Waste material was incinerated in a cupola at the rate of 1.8 tons/hr over a 4-hour period. Coke was used at a rate of 230 lb/ton of waste; limestone consumption was 170 lb/ton of waste with 6 pounds of fluorspar added per ton of waste. The slag and metal were found to be easily separated; the metal phase contained 0.3% copper.

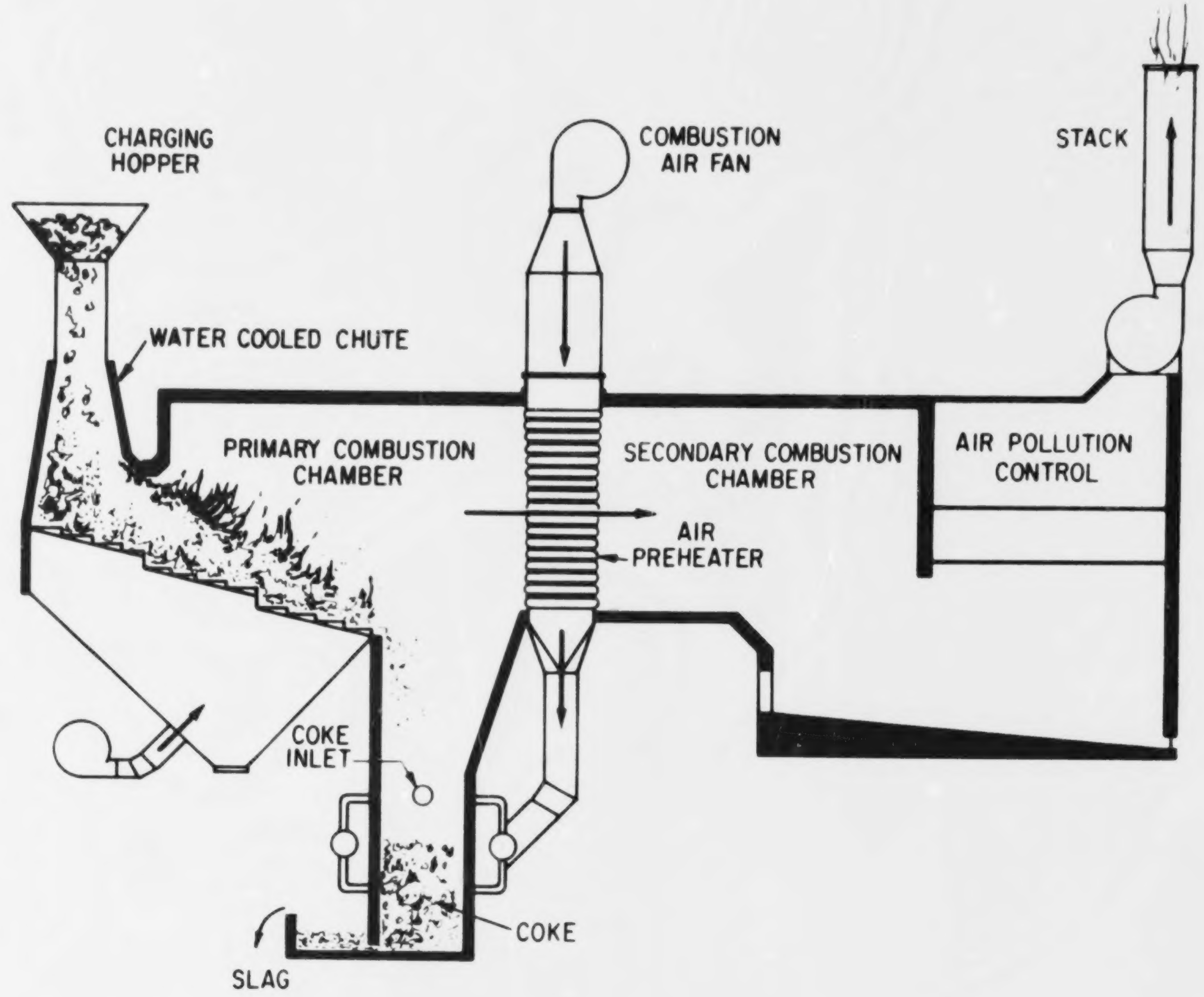

CHARGING HOPPER
COMBUSTION AIR FAN
STACK
WATER COOLED CHUTE
PRIMARY COMBUSTION CHAMBER
SECONDARY COMBUSTION CHAMBER
AIR POLLUTION CONTROL
AIR PREHEATER
COKE INLET
COKE
SLAG

FIGURE VII–39 FERRO-TECH SYSTEM

### b. *Advantages and Disadvantages*

The unique advantages of the Ferro-Tech system, in addition to those given in the general presentation, are as follows. The complete Ferro-Tech total incineration system is essentially a conventional incinerator with an integrated melting furnace, which serves to minimize the technological risk and probably allows continued operation if the melting furnace goes out of service. If a high degree of burnout can be achieved on the grate, no particular difficulties should be involved in developing a workable coke-fired melting furnace. It is noteworthy that conventional metallurgical techniques can be used successfully in the slagging of incinerator residue. The proposed water-cooled, refractory-lined melting furnace is similar in design to water-cooled cupolas. Water cooling should enhance refractory life at the sacrifice of some thermal efficiency in the melting furnace. Unusual particulate entrainment problems are not expected. Since only the melting furnace combustion gases are subjected to the slagging temperatures, only those gases would have any higher $NO_x$ content than conventional incinerator flue gases.

The fact that the grate system is not eliminated, so that no investment or maintenance saving accrues, represents one of the disadvantages of the Ferro-Tech concept. Also, the potential flue gas volume reduction is not so great as in the other slagging systems if a 90% burnout is to be achieved on the grate. In addition, auxiliary heat, in the form of coke, is required for the process, thus increasing the operating costs.

### c. *Problem Areas*

In addition to the general considerations, slag fluidity and drainage may present a problem in this process, particularly since the degree of burnout on the grate will vary with refuse moisture content. Also, although water cooling of the melting furnace should reduce deterioration, the refractory deterioration still represents a potential problem.

### d. *Economics*

The unit capital investment projected by Ferro-Tech for a 150-TPD system is reported to be $7800 per daily TPD. This capital investment includes all normal plant components and the necessary coke and limestone receiving and handling equipment. This cost is slightly higher than the average value for conventional systems of this capacity, as would be expected due to the added features of this system, but is still within the range of costs of conventional continuous systems. The incinerator melting furnace and associated equipment comprise about 30-40% of the total system cost. A 50% increase in the cost of these components, over the costs projected by Ferro-Tech, would put the system within the upper limit of the cost range of conventional systems of this capacity: about $9000/TPD or $2000/TPD higher than the average value.

A full-scale unit is projected to operate using 150 pounds of coke and 200 pounds of limestone per ton of refuse. At $20/ton for the coke and $6/ton for the limestone, the additional operating costs for this process are $1.50 plus $0.60, respectively, or $2.10/ton of refuse. If fluorspar is used at a rate of 1 pound/ton of refuse, a negligible additional incremental expense (about $0.02/ton of refuse) would be incurred.

Comments previously made regarding the by-product value of the recovered metal and the solidified ash are appropriate here. Slow cooling of the slag may result in the production of a more valuable aggregate than that produced by water quenching of the molten material.

### *(5) Electric Arc Slagging*

#### *a. Process Description*

The arc-slagging process, as proposed by Arthur D. Little, Inc., involves the use of an electric arc crucible furnace for fusion of the ash residue from a conventional incineration process. The slagging furnace can be installed as an add-on unit for either existing or new installations.

A suggested configuration is shown in Figure VII-40. Hot residue can be fed directly from the grates, or via a conveyor from a residue-holding bin, to the slagging furnace with subsequent rapid- or slow-cooling of the fused material and separation of the by-products, as in other slagging processes. The process is simple in concept and can be used without interfering with or otherwise affecting normal incineration processes. In comparison with other concepts utilizing augmented combustion temperatures to attain slagging conditions, the flue gas temperatures and flow rates for the arc-slag process are similar to those found in conventional furnaces. As a result, the particulate and nitrogen oxide pollutant loading should be unchanged.

Since only the incombustible residue has to be brought to slagging temperatures, the energy requirement for slagging is lower than for processes which involve slagging and incineration in the same operation. The amount of energy required in the arc-slagging process depends upon the temperature of the residue as fed to the slagging furnace. For residue available at 1700°F, 180,000 Btu's are required per ton of refuse (22% inerts). If the residue is permitted to cool down to essentially room temperature prior to feeding to the slagging furnace, the

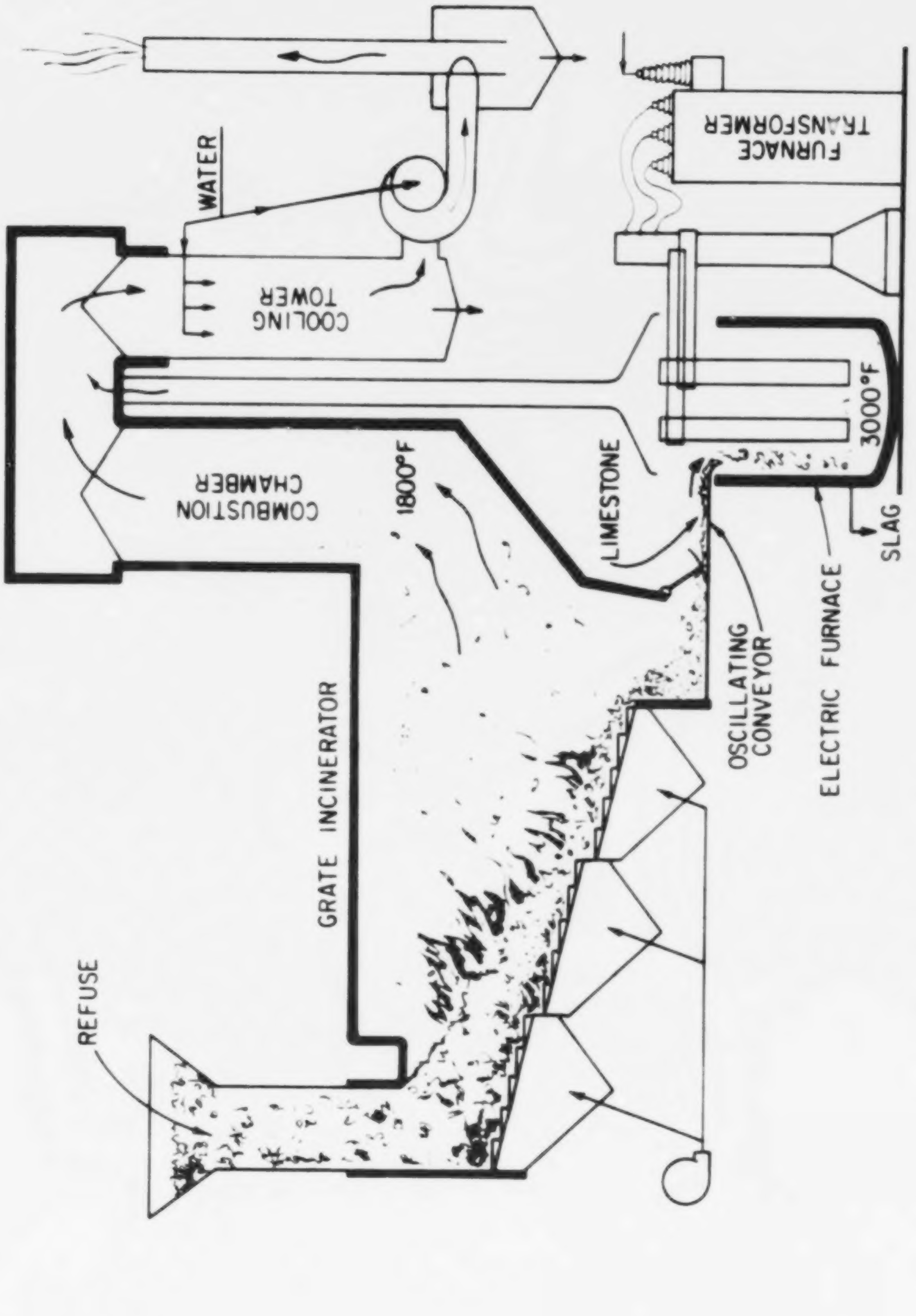

REFUSE
GRATE INCINERATOR
COMBUSTION CHAMBER
1800°F
LIMESTONE
OSCILLATING CONVEYOR
ELECTRIC FURNACE
SLAG
3000°F
COOLING TOWER
WATER
FURNACE TRANSFORMER

FIGURE VII–40 ELECTRIC FURNACE SYSTEM

energy required increases to 350,000 Btu/ton of refuse. Note here that the energy requirement is independent of the moisture content of the refuse and depends only on the noncombustible content of the refuse, or the pounds of material to be fused per ton of refuse burned.

For the case involving a cold residue feed to the slagging furnace, an installed furnace power capacity approaching 1000 kilowatts would be required to service a 200-TPD incinerator. The furnace could be designed for a proportionately lower power capacity if high incinerator residue temperatures were a design objective for the plant, as in new installations.

### *b. Advantages and Disadvantages*

In addition to the advantages and disadvantages given in the general presentation, the following unique comments apply: the arc-slag process can be used in new or existing conventional incinerator installations as the interface between the incinerator and the arc furnace is flexible. Thus, the arc slagging process can be operated with a minimum of interference or influence on the conventional incinerator operation. If the slagging furnace is designed to handle cold residue, it can be run almost independently of the incinerator, taking its charge from an incinerator residue storage bin. This implies greater reliability for refuse disposal.

The slagging process would not contribute to the solids load on particulate removal equipment and would not increase the gaseous pollutant emissions of the incinerator. No auxiliary fuel is burned and little or no gases would be emitted from the high-temperature arc furnace. As a result, there would be no significant additional heat load on gas cooling equipment; the only additional heat input would be vent gases from the slagging furnace.

The disadvantages of the arc-slag system are based primarily on its substantial use of electrical power and the special operating skills which are required for furnace operation. The effect of the increased use of electricity on plant operating costs is somewhat less than for alternative slagging concepts as only the residue (no combustion gas) must be brought to slagging temperatures.

### *c. Problem Areas*

The unique problems involved in implementing the arc-slag concept concern refractory and electrode maintenance. Slagging furnace refractory deterioration must be carefully considered in the system design. Although water cooling can be used (creating a chilled slag "refractory" protection), this is accomplished at a sacrifice in the use of electricity. Electrode deterioration and maintenance may be high but should be controllable.

### *d. Economics*

The arc furnace needed to service a 200-TPD incinerator for slagging cold residue is estimated to cost about $200,000 installed or about $1,000/TPD of incinerator capacity. For new installations the incremental investment would be less because of the reduction in the size of the residue-handling equipment.

The power consumption for slagging of cold incinerator residue in a three-phase electric arc furnace is about 140 kw-hr per ton of refuse containing 22% incombustibles; at $0.015/kw-hr; this corresponds to an additional operating cost of $2.10 per ton of refuse consumed. If the residue is available at 1700°F, this incremental operating cost is reduced by about 50%. In addition to the electric power costs, a small additional cost for limestone flux may be required. Electrode consumption rates are not known, but could approximate $0.40/ton of refuse. Arc furnace refractory maintenance would also add to the operating costs.

## *(6) Cyclonic Slagging Furnaces*

### *a. Process Description*

Figure VII-34 suggests that refuse combustion near the stoichiometric point can develop temperatures where residue will fuse. Requirements for such a process include intense mixing and high heat release rates. A number of such process concepts, aided in some cases by use of combustion preheated by heat exchange with the flue gas, are now under development. The SIRA process, now undergoing pilot testing in California and reported under study at General Electric Corporation, and an incineration system proposed by Incineration, Inc., all depend upon such design principles. The following is a brief description of the SIRA system as an example of this type of system.

The basic SIRA process is shown schematically in Figure VII-41. In operation, refuse which has been shredded and cleaned of metal and glass is pneumatically conveyed and burned, using preheated air, in a cyclonic-type combustor. Molten slag residue is discharged from the furnace. A pilot plant unit has been constructed and operated using shredded municipal refuse by the SIRA Corporation at its test facility in Los Gatos, California. At the present time, however, no public data are available for evaluation of costs, reduction efficiency, and the like.

### *b. Advantages*

Much higher heat release rates (Btu/cu ft-hr) are expected for cyclonic furnaces of this type in comparison to conventional incinerators. Consequent savings in furnace costs would be expected. In addition, operation near the stoichiometric point will result in minimum gas volumes for air pollution control.

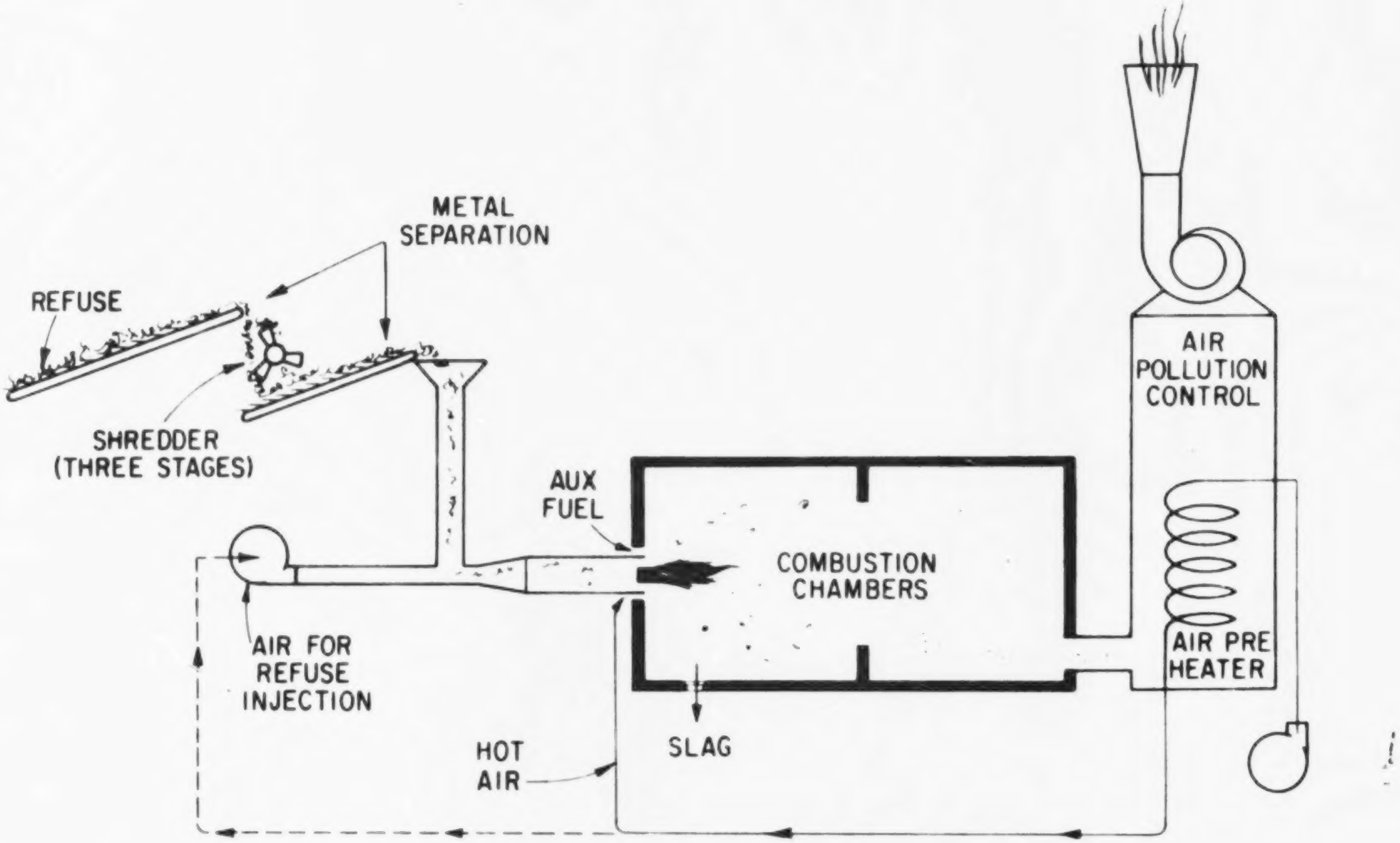

METAL SEPARATION
REFUSE
SHREDDER (THREE STAGES)
AUX FUEL
COMBUSTION CHAMBERS
AIR POLLUTION CONTROL
AIR PRE HEATER
AIR FOR REFUSE INJECTION
SLAG
HOT AIR

FIGURE VII–41 SIRA SYSTEM

### c. *Disadvantages*

The air pollution problems associated with these processes should be similar to the Type I slagging systems, although pneumatic refuse feeding suggests that still higher particulate furnace emissions will be observed. The intense mixing characteristic of cyclonic combustors should assure nearly complete burnout of combustible pollutants. As suggested above, it is speculated that nitrogen oxide emission may be somewhat higher than in conventional systems operating at comparable refuse disposal rates.

Processes based on this design concept can be expected to require more sophisticated control systems to maintain slag fluidity with changes in refuse composition. Special operator skills may also be required for stable operation. Pretreatment of the incoming refuse to remove metal and glass, if required for such systems (apparently necessary for the **SIRA** process) adds substantially to the capital and operating costs. The size reduction costs developed in Appendix A, for example, suggest that shredding to the 1/2-inch top-size which, it is understood, is used in the **SIRA** process, would add almost $3 per ton to the operating cost. Additional costs would be incurred for metal and glass segregation equipment.

### d. *Problem Areas*

Problem areas for incineration systems of this type are expected to lie primarily in aspects of combustion control and materials of construction. Furnaces operating at high heat release rates are sensitive to relatively small changes in fuel heating value and slag viscosity characteristics. The great variability found in municipal refuse suggests, therefore, that either fast-acting combustion control systems or intensive refuse blending will be required for stable operations. Material problems in the primary furnace are anticipated due to the severe erosive and corrosive (fluxing) action in combustion systems of this type.

## 5. Fluid-Bed Incineration

The petroleum and petrochemical industries have established fluidized bed technology as a powerful tool for performing gas and liquid phase reactions, especially the former, wherein a number of process variables and controls can be optimized. The high heat transfer and reaction rates which can be achieved in fluidized beds suggest their application for the incineration of refuse to achieve good burnout of residue and combustible air pollutants.

When a gas (such as air) is passed uniformly through a static bed of small, solid particles (such as sand), the decrease in static pressure through the bed, $\Delta P$, is found to vary directly with the velocity of the gas (usually calculated on the empty cross-sectional area of the containing vessel) until the frictional drag on the solid particles buoys the whole bed upward. In practice, the bed of solid particles is usually supported on a retaining grid through which the fluidizing gas passes. Figure VII-42 shows the effect on bed height and pressure drops from increasing the gas velocity.

When fluidized, the bed solids move in a more or less random fashion and, as a mass, behave very much like a boiling liquid; that is, the bed's upper surface will be located at a definite point and will become ebullient due to bubbles of gas breaking through the surface. In this state, if a hole is made in the vessel wall or a valve opened below the level of the bed surface, the solid particles will flow from the vessel as would a liquid. It was from this state of fluid-like behavior that the name fluidized bed was derived.

In the fluidized state, solid particles and gas are in continuous and intimate contact. Low energy collisions of the particles with each other and with the vessel walls or other surfaces cause a scouring action, preventing the occurrence of stagnant layers around these surfaces. The low energy level of these collisions does not usually create very serious problems of particle attrition or erosion of vessel walls or other surfaces which may be placed in the bed. Because the solid particles are in continuous contact with the gas phase, are well mixed, and have a large total surface area per unit volume of solids, it is not surprising to find high rates of heat and mass transfer occurring. Consequently, the fluidized bed concept has already begun to be applied to the thermal destruction of waste solids.

Burning deposited coke and other combustible substances from solid catalyst had long been practiced in the petroleum industry when research and development work was undertaken in both the U.S. and Germany on the use of the fluidized bed as an incinerator for waste solids. The concepts stemmed from the use of the fluidized beds in such operations as calcining of lime, fluid coking, burning of metallic sulfides, roasting of ores, etc. Early entrants into the field were the Container-Copeland Corporation with fluidized bed incineration of high solids content waste liquors from papermaking, Dorr-Oliver with incineration of sewage sludge solids in a fluidized bed, and Lurgi Gesellschaft für Wärme and Chemotechnik with fluidized bed incineration of oily sludges from petroleum refinery waste treatment processes.

### a. Current Applications of Fluid-Bed Incineration for Waste Disposal

All commercial fluid bed incineration applications are limited to destruction of relatively homogeneous liquids, slurries, or semi-solid mixtures, such as dewatered sewage sludges. All of these applications are strikingly similar in operation. They were used to thermally destroy waste which contained noncombustible solids that would either form (a) bed particles, which could be removed by

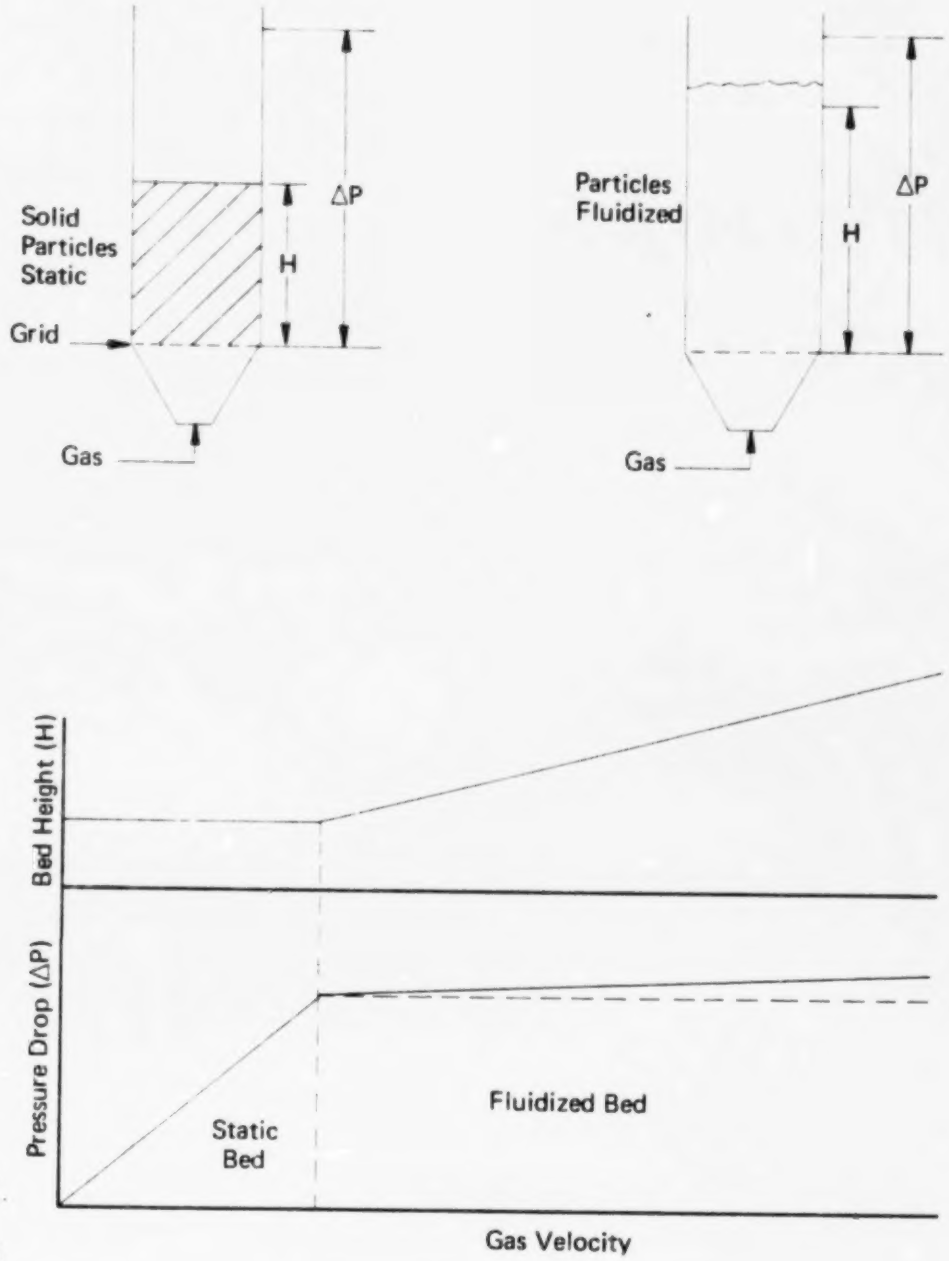

Solid
Particles
Static
Grid
Gas
H
ΔP
Particles
Fluidized
Gas
H
ΔP
Bed Height (H)
Pressure Drop (ΔP)
Static
Bed
Fluidized Bed
Gas Velocity

FIGURE VII–42 ILLUSTRATION OF FLUID BED PRINCIPLE

overflowing the bed, or (b) solids, so finely divided that they were carried out of the fluidized bed (elutriated) by the flowing gases. Consequently, the major process variations found between the different suppliers were in the feed methods and mechanisms employed for introducing the wastes into the fluidized bed and the type of equipment used to remove excess solids from the bed or from the off-gas streams. Use of the latter equipment was dictated primarily by the methods required for further handling or disposal of the removed solids.

The basic components of fluidized bed incinerators are typified in Figure VII-43. The use of the fluidized bed technique for incineration of wastes is based either on the deposition of inert, noncombustible portions of the waste on solid particles of the same inerts while burning off the combustible portions, or on the use of a bed of inert solids, typically sand, in which the solids burn and from which the noncombustible portion of the waste is elutriated by the fluidizing air.

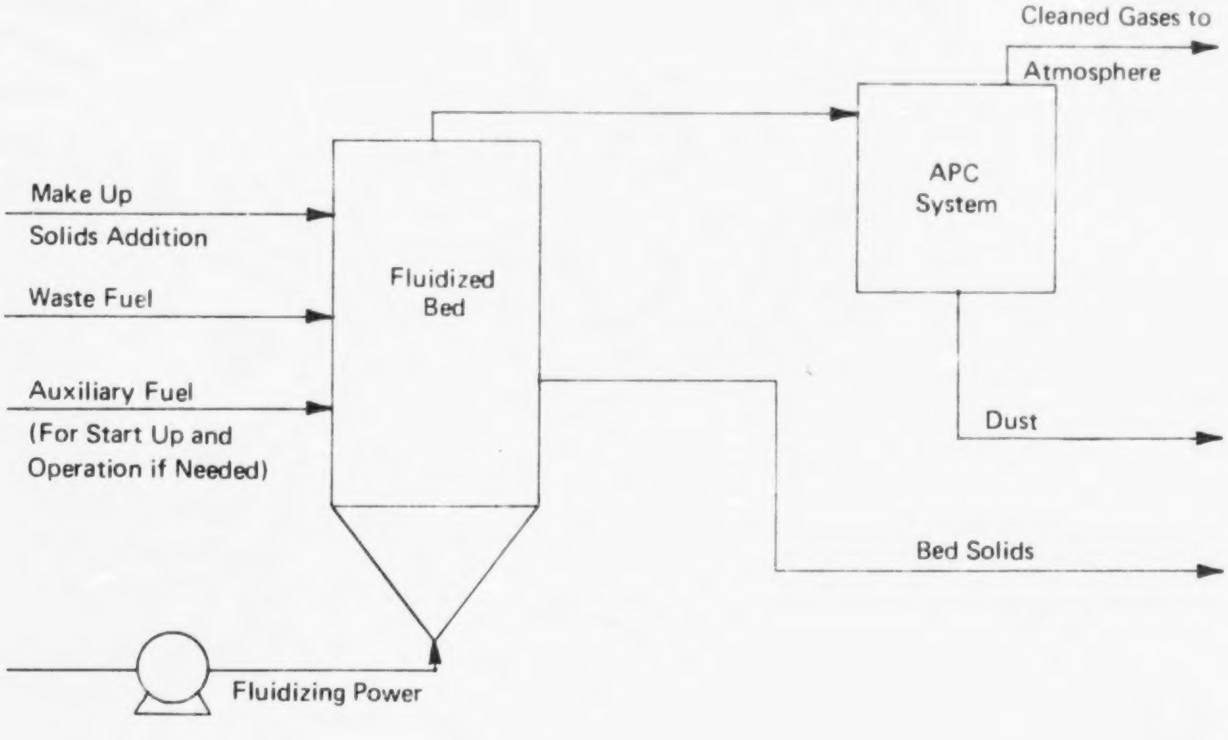

Cleaned Gases to
Atmosphere
APC
System
Make Up
Solids Addition
Fluidized
Bed
Waste Fuel
Auxiliary Fuel
(For Start Up and
Operation if Needed)
Dust
Bed Solids
Fluidizing Power

FIGURE VII–43 FLOW DIAGRAM OF FLUID BED SYSTEM

The state-of-the-art of fluidized bed incineration of sludges and liquid wastes is best described by considering the fluidized bed operating parameters. Once fluidization has been established, it is apparent from Figure VII-42 that increasing the rate of gas flow through a bed of fixed cross-sectional area will result in expansion of the bed. This expansion means that the distance between individual particles becomes greater or, conversely, the bed void fraction (i.e., that fraction of the bed not occupied by solid particles) increases. Of course, the velocity can be increased to a point where the solid particles are blown from the bed. This velocity is known as the terminal velocity and is a unique function of the particle dimensions, shape, and density, and the gas density and viscosity. For a bed of uniform particles, this is a definite velocity, all other factors remaining constant. In an actual fluidized bed situation, particle dimensions may vary such that the smallest particle is below its terminal velocity at the gas velocity used, and the largest is above its incipient fluidization velocity. A typical bed-size distribution for the fluidized sand beds used in sewage sludge incinerators will be found to have approximately a Gaussian distribution around a median particle diameter, the median diameter being compatible with the operating parameters of particle density, fluidization velocities, system pressure, and the viscosity of the gas in the operating temperature range. Several texts[70, 71] are available which describe the characteristics of fluidized beds with nonuniform sized particles.

Selection of the operating conditions and establishing the characteristics of the fluidized bed for incineration of waste materials is largely proprietary information. However, some guidelines can be established from published information and from a knowledge of the fundamentals of fluidization and combustion. Of primary importance is the selection of a range of particle sizes which can be utilized to achieve commercially useful ranges of operation. For example, if the median particle diameter of the bed is too small, the volume of air required for fluidization, while retaining the bed within the vessel, will be so low that the rate of incineration is economically impractical. Furthermore, it is known that beds with small median particle diameters are especially susceptible to agglomeration if the waste is not finely dispersed as it enters the bed. Conversely, large median particle diameters permit high fluidizing air velocities without carryout of particles but have such a low particle surface area per unit volume of bed that it becomes impossible to retain the waste for adequate time for complete incineration. Thus, the fluidized bed incinerator must still rely on the basic concepts of time, temperature, and turbulence for its effectiveness. As a consequence of these limitations, the particle size range needed for most practical operations will be found generally between 4 and 100 mesh (Tyler screen series) with the mass median diameter most probably between 20 and 60 mesh.

Fluidized beds have excellent heat-transfer characteristics over wide ranges of operating conditions. The foremost characteristic is the uniformity of temperature throughout the bed. If the fluidizing gas is either hotter or colder than the fluidized bed, it will be brought quickly to the bed temperature. In experiments at the Battelle Memorial Institute, gas at a temperature of 12,000°F was injected into a fluidized bed; within a vertical distance of 1 inch the temperature had dropped to the bed temperature, 2000°F. Temperature measurements in fluidized beds where fuels are being burned show the same general temperature uniformities. As would be expected, the heat-transfer rate is primarily a function of particle diameter and fluidizing velocities, and, in addition, the physical properties of the gas and fluidized solids.

Limitations on upper temperature levels are determined generally by the temperature characteristics of the fluidized bed particles and the waste being incinerated; it is necessary to operate at a temperature of about 100°F below the minimum fusion point of the system to avoid bed particles agglomerating to a size larger than can be fluidized. Although it is possible to operate fluidized bed reactors in which incipient fusion of bed particle surfaces may be occurring, this practice is not recommended in fluidized beds used for incineration. The minimum temperature for satisfactory incineration is found generally to be in the 1100° to 1300°F range as this range will ensure destruction of odors. For some refuse ash mixtures, this may lie near the fusion point.[74]

A major advantage of the fluidized bed incinerator is the thermal inertia that is present in the mass of solid particles. This results in the refuse feed being brought quickly to incinerator temperatures and ignited. Burning of pyrolysis products will occur on the surfaces of the bed particles and in the void spaces, releasing the heat of combustion within the bed and thereby maintaining the bed temperature. As previously mentioned, a range of particle sizes and fluidizing velocities that have practical operating limits must be chosen. If the fluidizing velocities are too high, i.e., the void fraction of the bed is high, the retention time of wastes in the bed may be too short to attain complete combustion with the result that the remaining combustion occurs in the space above the bed as an afterburning effect. This condition is especially prevalent if wastes contain a significant fraction of volatile components, such as oils, and the incinerator is being operated at high fluidizing velocities. The major consequence of this condition is a decrease in the bed temperature to a point where the incoming wastes can no longer be brought to ignition temperature. At the present state of development, operating temperatures for fluidized bed incineration of wastes are usually in the 1200° to 1600°F range.

Operating conditions in a fluidized bed incinerator will depend upon a number of variables discussed previously and especially upon the lower heating value of the waste. Inert, noncombustible portions of wastes are usually of small concern in the thermal balances. It is possible to attain complete incineration of solid wastes such as sewage sludge solids with a minimum amount of excess air, often as little as 10% above theoretical. As the percentage of oxygen in the off-gases decreases, the possibility of carbon monoxide formation increases. However, fluidized bed incinerators are operating in the range of 2 to 4 percent oxygen in the off-gases with complete combustion achieved. As with any incinerator, the thermal balances around the fluidized bed and ancillary heat exchange equipment are paramount to any design.

Although fluidized beds of solids have excellent mixing characteristics, the manner of introduction of the waste, be it solid, liquid or gas, is of great importance especially as the cross-sectional area of the incinerator increases, i.e., as the total capacity increases. The methods used for feeding wastes depend upon their physical and thermal characteristics. Fluid wastes may be pumped into the bed through open-ended pipes, sprayed downward onto the bed, or sprayed into the bed by the use of air-liquid nozzles. Solids are forced into the bed through ports by compressive screw feeders, by progressing cavity pumps, or by other feeders which discharge into the bed from above or from side-entering chutes. The types and number of feed points must be determined largely through experience, and this area is one where proprietary information is most important. If wastes are introduced in large volumes at a limited number of points, the capability for the bed to achieve satisfactory dispersion will be exceeded and combustion efficiency will be limited. Because the density of the fluidized bed is often in the same range as the waste feeds, i.e., 45 to 70 lbs/cu ft, solids such as sewage sludges can be fed through ports as large as 6 to 8 inches in diameter with no apparent effect on incineration capacity.

A large number of fluidized bed incinerators are operational for the incineration of dewatered sewage sludges, oily sludges, and various other liquid or semi-solid wastes. Those accommodating sewage solid and liquid sludge incineration use beds of inert solids (typically graded sand). The destruction of wastes containing a high content of noncombustible solids (such as the salts in paper-making wastes) results in continual particle growth and removal, with the particles serving as the bed material. Pilot plant investigations on the use of the fluidized bed incinerator for the combustion of refuse are under way in this country as well as Japan. Applicability of the fluidized bed concepts to the destruction of refuse is discussed in the following sections.

### b. Refuse Incineration in Fluid Beds

Use of the fluidized bed technique for incineration of homogeneous wastes such as oil and sewage sludges is well documented in the United States and German technical literature.[47-53] Small-scale, mechanically agitated fluidized beds have been tested in Japan.[54,55] The fluidized bed incineration of municipal refuse is being investigated on a pilot plant scale at West Virginia University.[56] Feasibility studies for high-pressure fluidized bed incineration of municipal refuse have been made for a system recovering energy as steam or electricity and test evaluations of critical components are scheduled.[57] It is understood that some process equipment manufacturers are conducting pilot plant tests based on separating the large-size, noncombustible portions from municipal refuse and producing a filter cake-like material for feeding to incinerators. At the present time, there are no fluidized bed incinerators operating in the field of municipal refuse incineration.

*(1) Fluid-Bed, Incinerator-Feed Preparation.* Fluidized-bed incinerators have been applied, as previously described, to wastes which are more homogeneous in composition than municipal refuse. Because refuse is composed of disparate materials of widely varying physical properties, one of the most difficult technical problems which must be overcome before fluidized-bed incineration of refuse will be feasible is the preparation of the refuse to enable feeding to the incinerator. Some of the noncombustible particles cannot be elutriated from the bed by gases. Thus, their effect on the operation of the fluidized bed must be considered in specifying refuse preparation procedures. Although large-diameter solids with particle densities near the density of the fluidized bed will be supported by the ebullient action of the bed, ultimately either these solids or higher density solids of smaller diameter will tend to settle to the bottom of the bed. Conversely, very small diameter solids are often found to accumulate in a fluidized layer on the surface; this occurrence has little operational significance.

Although large substances, such as oranges and celery stalks, will not settle immediately to the bottom of a fluidized bed of sand particles, materials of higher density, such as steel, small rocks, etc., will settle rapidly onto the air-dispersing grid plate. Small amounts of these dense materials will not cause significant operational problems; however, large amounts will accumulate and tend to destroy the operational characteristics of the fluidized bed incinerator. Continuous removal of large amounts of dense particles from the bottom of a fluidized bed presents severe mechanical problems, and it is often necessary to shut down and dump the bed to achieve satisfactory removal. Alternatively, low density materials with large surface areas, e.g., paper, could be elutriated from the fluidized bed before their destruction and carried into the off-gas cleaning equipment.

Preparation of refuse for feeding a fluidized bed can be based on either of two concepts. The first concept is to reduce all parts of the refuse to a size and shape at which noncombustible particulates are readily removed from the bed by overflow or by specially designed equipment; the second concept is to remove those noncombustible portions that may accumulate prior to feeding the refuse to the bed. A requirement of either preparation system concept is to reduce the refuse to a form which can be successfully consumed in the incinerator. It is expected that particular attention must be given to comminuting paper and plastic materials to a size adequate for destruction within the fluidized bed. This means that these materials must not be elutriated from the bed into the off-gas system or must not contribute to fusing bed particles into large agglomerates which might settle out before the binding substance is destroyed thermally.

Various combinations of shredders and other comminuting devices can be conceived for the feed-preparation system. Of special interest is pulping of shredded refuse with water, followed by the separation of heavy particulates, before feeding the pulp into the fluid bed incinerator. This method might overcome the problem of solids buildup in the bed as well as prepare the feed in a form readily fed to the incinerator. Since a fluidized bed incinerator operates most efficiently within rather narrow limits of combustible content in the feed, this system is believed to be especially attractive for use with a fluidized bed incinerator. A flow diagram for such a preparation system is shown in Figure VII-44.

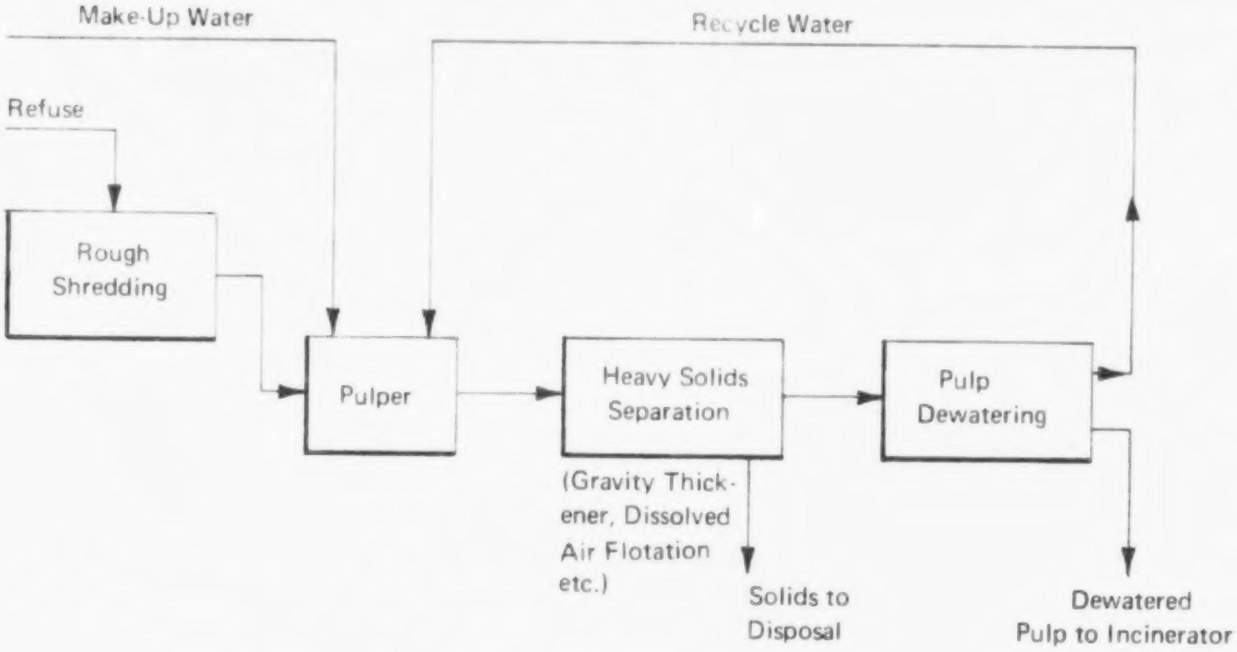

Make-Up Water
Recycle Water
Refuse
Rough Shredding
Pulper
Heavy Solids Separation
Pulp Dewatering
(Gravity Thickener, Dissolved Air Flotation etc.)
Solids to Disposal
Dewatered Pulp to Incinerator

**FIGURE VII–44 FLOW DIAGRAM OF PROCESS TO PRODUCE PULPED REFUSE FEEDSTOCK FOR FLUID-BED INCINERATION**

*(2) Anticipated Bed-Operating Characteristics.* Of the two operational modes of fluidized bed incinerators, i.e., either the use of an inert solid medium, such as sand, or the production of the fluidizable solids from the waste, the inert solid medium method of operation has the most promise. Suitably sized sand, preferably having a high silica content, will be the first choice of bed material because of its wide availability, relatively high fusion temperature, and low cost. Chemical reactions between the sand and components of the refuse, e.g., sodium compounds such as sodium carbonate, may cause problems by fusion of sand grains or by accelerating decrepitation. Also, operational temperatures must be maintained considerably below the fusion temperature of noncombustibles which might build up in a bed.

Noncombustible substances are preferably removed from fluidized bed incinerators by carryout in the off-gases for subsequent removal by air cleaning devices. These solids will have mass median particle diameters in the region of 200 Tyler mesh with a significant fraction in the range of 5 to 10 microns in diameter. The particle size of the entrained dust will depend upon the nature of the waste incinerated. The type of air cleaning equipment installed on the fluidized bed incinerator will depend upon local air pollution codes and upon the methods chosen for solids disposal. The size range of the solids removed from a fluidized bed incinerator is expected to be relatively uniform. However, they may have a higher bulk density than solids from other incinerators. On the other hand, the relatively small size of the solids may contribute to disposal problems such as wind blowing from land-fill operations.

Although fluidized bed incinerators have high heat release rates per unit volume of bed and operate with low percentages of excess air, wide variability in the combustible content of the refuse may create control problems. Temperature control can be maintained readily by spraying water into or above the fluidized bed. However, if a large slug of highly combustible material, such as oil-saturated wastes, entered the incinerator, smoking and excessive temperatures could easily result. Other methods of controlling temperature would be to install heat exchange equipment (e.g., water-cooled tubes in the bed) or increase the flow of air. However, the former method does not have rapid response and the tubes may be subjected to fouling in an incinerator. The latter is limited by the carryover of bed solids at high gas velocities as well as the need for controlling air flows over a significant range. Because refuse often has a high energy content with respect to its moisture content, operation at the desired temperature levels for a fluidized bed incineration (1600°F) requires that temperature control methods be provided.

The magnitude of the heat removal required when incinerating (at 1600°F) a refuse having a higher heating value of 9000 Btu/lb of combustible is shown in Figure VII-45 for 0, 25, and 50% excess air both with and without preheating of the fluidizing air. From these curves, it is apparent for even 50% excess air that the moisture content of the refuse can be 50% without requiring the use of auxiliary fuel.

*(3) Advantages of Fluid Bed Systems for Refuse Incineration*

- Simplicity of construction. The incinerator consists of a vertical cylindrical chamber with no moving internal parts. High volumetric heat release rates can be achieved in the fluid bed units.

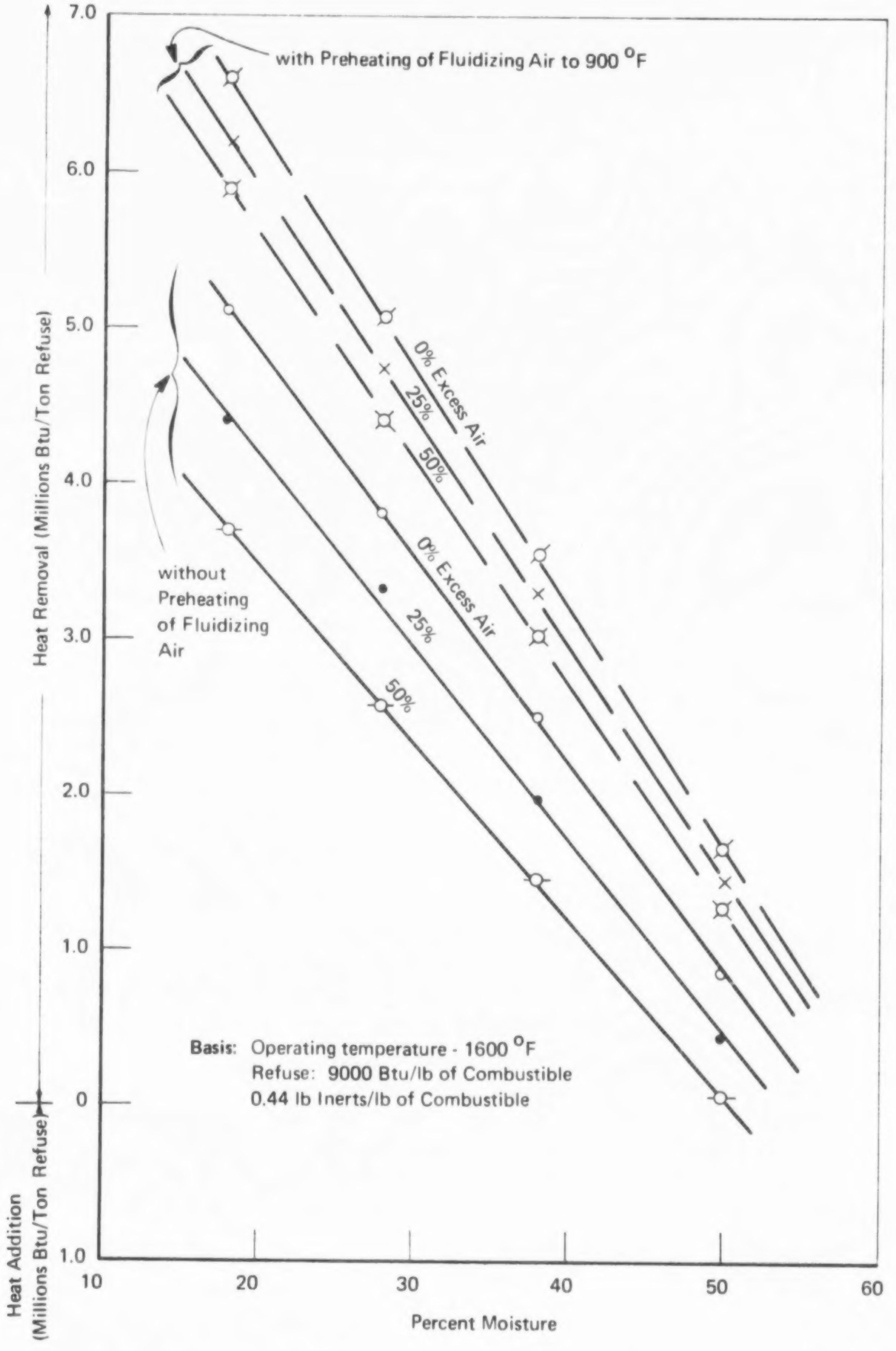


FIGURE VII–45 HEAT REQUIREMENTS FOR FLUIDIZED BED SYSTEMS

- Complete combustion at relatively low temperatures. Complete combustion of low heating value wastes is possible at about 1600°F, because of the excellent heat- and mass-transfer characteristics of fluid beds. As a result, combustible pollutant emissions should be small.

- Low $NO_x$ emissions. The low operating temperatures and absence of local high temperature combustion zones or, hot spots, should result in the production of negligible amounts of nitrogen oxide.

- Low flue gas volumetric rates. Complete combustion at excess air rates as low as 10% results in a very significant reduction in the amount of gas to be cleaned, relative to conventional incinerators operating at excess air rates up to 200%.

- High heat sink capacity. The large thermal capacity or inertia of the bed tends to damp out moderate temperature or other operating fluctuations due to short-term variations in feed characteristics.

- Ease and efficiency of intermittent operation. The excellent heat retention capabilities of a static bed of solids (with adequate wall insulation) enables shutdown of a fluidized bed incinerator for extended periods without the temperature dropping below a satisfactory level for immediate startup. If substantial cooling has occurred, only a short reheat time is usually necessary prior to beginning incineration.

*(4) Disadvantages*

- Feed preparation requirements. Considerable feed preparation is required to assure retention of particles in the bed, complete combustion of refuse, and removal of incombustibles.

- Flue gas particulate loading. The high gas velocities will result in high solids loading, requiring more efficient particulate removal equipment to achieve emissions comparable to those from conventional incinerators. The higher efficiency requirement could easily offset the savings due to gas volume reduction if comparable particle-size distribution particulate is produced in the fluid bed.

- Operational complexity and sensitivity. Operation of the fluidized bed is more complex and sensitive to variations in feed composition and heating value than conventional incinerators. Rapid and large increases in the feed heating value could result in temperature excursions large enough to flux the bed material; variations in refuse composition could also result in fluxing of the bed material. Although the bed can be controlled to minimize these effects, the system must be considered more sensitive and complex than conventional systems and will require more highly trained operators.

- Unit size limitation. The maximum single-unit size for refuse incineration is estimated to be 50 to 60 TPD, the size limitation corresponding to the maximum cross-section consistent with good bed distribution. This size limitation is very unfavorable.

- High power consumption. Power consumption will be high relative to conventional incinerator systems due to power requirements for fluidizing gas blowers.

- High cost. The cost per TPD for fluid bed incineration is prohibitively high (see below).

*(5) Problem Areas.* As discussed at length above, several difficult technical problems must be solved before application of fluid beds to municipal refuse incineration can be considered feasible. It should be recognized in this regard that many of the same problems apply to industrial applications of the fluid bed and that considerable financial and technical resources have already been expended in attempting (without clear success) to find solutions. The problems:

- Feed preparation requirements. Appropriate feed preparation techniques must be developed for proper retention, combustion, and removal of incombustibles from the bed with acceptable investment and operating costs. This is a major problem.

- Fusion of the bed. Combustion must be performed at a high enough temperature to assure elimination of odors, yet low enough so that refuse composition variations and temperature excursions do not result in fluxing or fusion of the bed.

- Removal of dense materials from the system. Objects too dense to be supported by the bed will drop out, accumulate on the grate at the base of the unit, and interfere with fluidization unless an appropriate removal mechanism is developed. Previous equipment development in this area has not been entirely successful.

- Control of bed temperature. Adequate controls must be provided to assure that large increases in refuse heats of combustion do not result in bed-temperature excursions. Refuse wet pulping or dry blending could solve this problem.

- Feed distribution. The problem of achieving an even distribution of feed into large diameter units must be overcome in order to avoid the necessity of multiple small unit installations to achieve large incineration capacities.

- Feed mechanism. Many attempts to feed refuse, especially into pressurized chambers, have met with failure due to burnback, jamming, or bridging. Refuse pulping with segregation of metal and glass may be helpful.

### c. Fluid Bed Incineration with Power Generation

The Combustion Power Company of Palo Alto, California,[57] is investigating the feasibility of using a fluidized bed combustor for incineration of refuse with the generation of electric power. The fluid bed operates at a pressure of about 100 psia, combusting the refuse and generating hot combustion gases to drive a gas-turbine electric generator. Operation of the fluid bed at elevated pressures should result in extremely high volumetric heat release rates.

The fluid bed has many advantages, as previously described, as equipment for combustion of solids and generation of high-temperature, high-pressure gases; the disadvantages and problem areas discussed above are also pertinent here. The expected problem areas have been recognized by Combustion Power:

- In-process particulate removal. Very efficient removal of the high level of particulate from the fluid bed exhaust gases must be performed prior to expansion of the high-temperature, high-pressure gases through the gas turbine. Almost complete removal of particulate above 5 microns must be accomplished to enable long-term operation of the turbine at an acceptable level of maintenance.

- In-process removal of corrosive combustion products. Corrosive combustion products, such as HCl, must also be eliminated from the gases prior to turbine expansion. The addition of limestone to the feed is being considered as a means of removing the HCl through a gas-solid reaction in the bed.

- In addition, the problems of high capital investment, refuse preparation, removal of inerts from the bed, feed distribution, bed fluxing, and temperature control must also be solved.

The problems to be solved for feasibility of fluid bed incineration of refuse, coupled with the very stringent gas-treating problems for applicability of gas-turbine power generation, constitute a very formidable, long-range development program.

Aspects of the process are in various stages of conceptual design or development. Fluidized bed combustion of municipal refuse is yet to be demonstrated.

d. Required Research

Because much engineering design and operational know-how is available for fluidization techniques, the required research and developments efforts necessary to determine the potential for fluidized bed incineration of refuse can be selective. The most important areas for research and development are outlined below:

1. The method of preparation of refuse feed for the incinerator must be determined, especially the aspects of handling and disposing of the noncombustible portions. Methods of removing refuse components, such as glass and metals, from either the refuse prior to incineration or from the incinerator itself must be demonstrated. Probably the most successful methods will prove to be either (a) grinding the refuse to a size range such that the aforementioned solids can be readily removed from the incinerator (probably about eight-mesh), or (b) removal of these solids prior to incineration by techniques such as coarse grinding, followed by water pulping to remove the heavy inert solids.

2. Feeding devices, especially for large-diameter beds operating with relatively shallow bed depth, will have to be developed to ensure adequate distribution of the solids in the bed so that the major portion of the heat of combustion is released within the bed and not in the disengaging space above the bed. For these results to be meaningful, it is recommended that the pilot plant incinerator have an inside diameter of at least 2 feet. This size is judged to be large enough both to overcome the difficulties of small size equipment and to provide realistic indications of the probable operational problems. An integral part of this test program should be the determination of the efficacy of additives such as limestone for removal of hydrogen chloride, sulfur dioxide, and the like.

3. High efficiency removal of particulates from high-temperature gases should be further investigated. Since this is primarily a materials of construction problem, candidate devices based on available materials should be tested by installation in the off-gas systems of fluidized bed incinerators or roasters presently operating on sewage sludges or metallurgical ores. A number of municipal sewage sludge incinerators where the necessary tests could be performed should be located and necessary test arrangements made. Further research and development work on the jet engine incinerator could then be performed upon successful development of the preparation system and the hot gas filtration system.

4. Successful completion of the above research and development objectives would provide the data for a careful appraisal of the relative economic merits of fluidized bed incineration of refuse. Based on present technology, the economies appear doubtful. If an economic case can be made at that time, however, construction and detailed testing of a fluidized bed having an internal diameter of 5 or 6 feet and designed for pressure operation, would be recommended. From this test facility would come sufficient design and operational information for commercialization of the concepts.

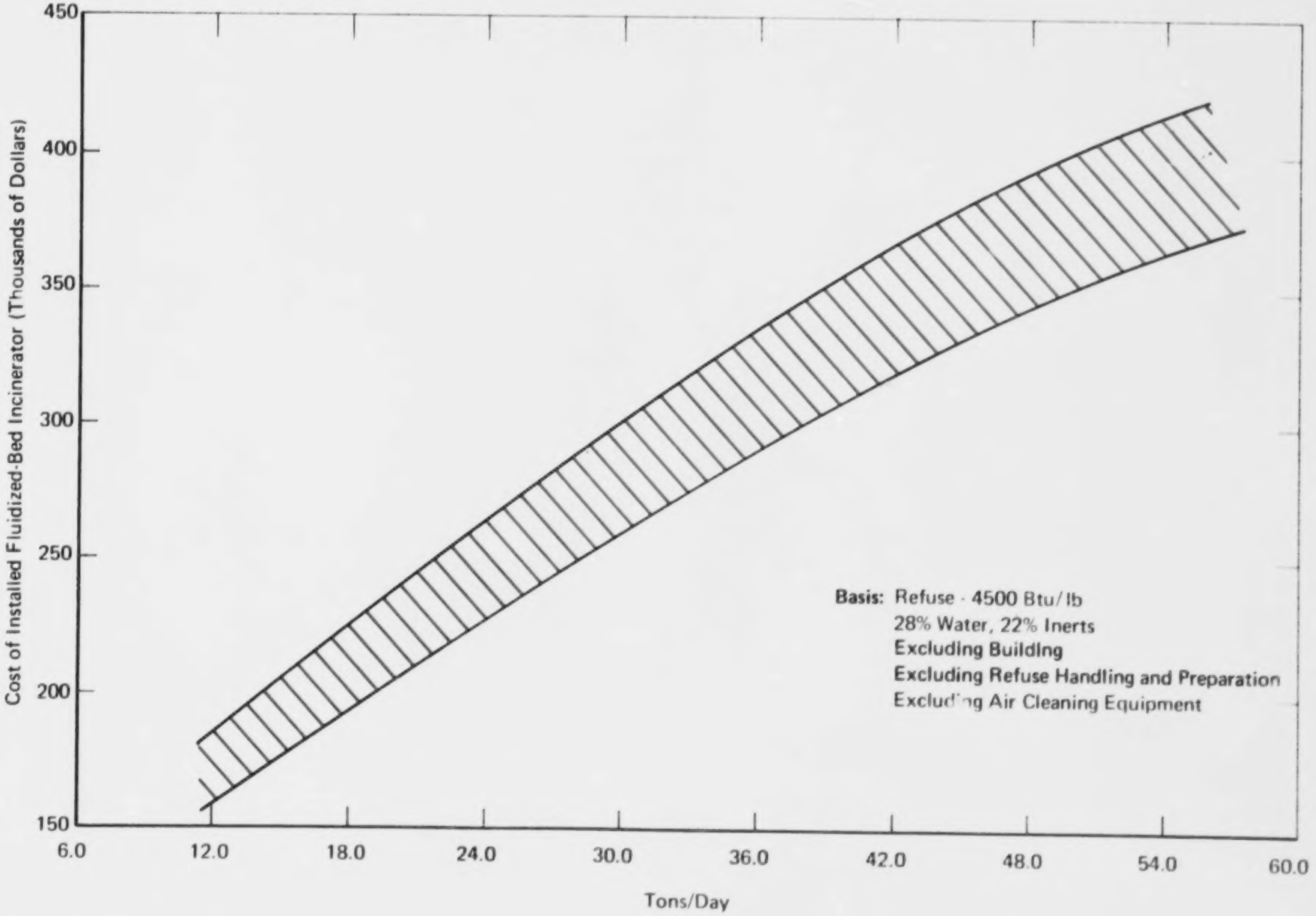
e. Economic Analysis

*(1) Capital Investment.* The estimated cost range for the installation of fluidized bed incinerators, using inert beds of solids is shown in Figure VII-46. These costs include all controls and a feed system based on the use of tapered screws, but do not include building, feed preparation, gas cleaning, and stack expenditures. The equipment size has been based on autogenous combustion, at 1600°F, of a refuse having a higher heating value of 9000 Btu/lb of combustible and a ratio of inerts to combustibles of 0.44. From previous thermal balances, the feed would be prepared to have a moisture content in the vicinity of 50 weight percent. The maximum daily capacity for a single fluidized bed incinerator is estimated to be between 50 and 60 tons of refuse having the composition noted on the curves. This limit is due to the difficulties involved in attaining good distribution of the refuse within large diameter fluidized beds operating with relatively shallow bed depths.

The following building area requirements are estimated for the fluidized bed incinerator, along with the feed mechanisms, fluidizing air blowers, and control panel:

| Capacity (tons/hr) | Area (ft) | Height (ft) |
|---|---|---|
| 0.5 | 15 x 25 | 35 |
| 1.5 | 22 x 30 | 42 |
| 2.5 | 30 x 35 | 50 |

The overall height includes allowance for off-gas ducting. The maximum height requirement for the incinerator proper would apply to about 60% of the floor area if no heat recovery equipment is installed.



**Basis:** Refuse · 4500 Btu/lb
28% Water, 22% Inerts
Excluding Building
Excluding Refuse Handling and Preparation
Excluding Air Cleaning Equipment

FIGURE VII–46 CAPITAL INVESTMENT FOR FLUIDIZED BED INCINERATORS

The capital cost estimates for installation of the complete fluid-bed incineration complex are given in Figure VII-47; multiple fluid bed units are used for plant capacities over 60 TPD. Cost curves are shown for subsystems: feed preparation and handling, fluid bed unit costs, building and electrostatic precipitator costs. The feed-preparation and handling system includes:

- crane
- refuse shredding
- pulping
- heavy solids separation
- pulp dewatering.

The fluid bed unit costs are the same as those given in the previous figure. The building costs include:

- excavation
- foundations
- building and structural supports
- refuse pit
- land improvements and access roads.

The electrostatic precipitator costs include all ducting and equipment directly associated with the particulate control equipment.

The costs are based upon preparation and incineration of a 50 weight percent solids pulp, with no heat recovery. For incineration of refuse with a moisture content of approximately 28%, the removal of heat from the bed, along with preheating of the fluidizing air, indicates that approximately enough steam can be generated for driving steam turbines powering the fluidizing air blowers. Of course, this mode of operation would require either a standby boiler for startup or auxiliary electrical motor drives. Estimates of the costs incurred to provide such a recuperative system are shown in Figure VII-48, and would be additive to the installed costs of the incinerator system shown in Figure VII-46. Since the pulping method of feed preparation offers the best likelihood of feasibility of fluid bed incineration of refuse, only this method was considered in the operating cost estimates.

*(2) Total Operating Costs.* Electric power consumption is estimated to be 70 kwh/ton of refuse incinerated in a fluidized bed not equipped for heat recovery. Installed blower horsepower is estimated to be 100 H.P. (hourly ton of capacity) for such an incinerator and 120 H.P. for an incinerator equipped with heat recovery equipment.

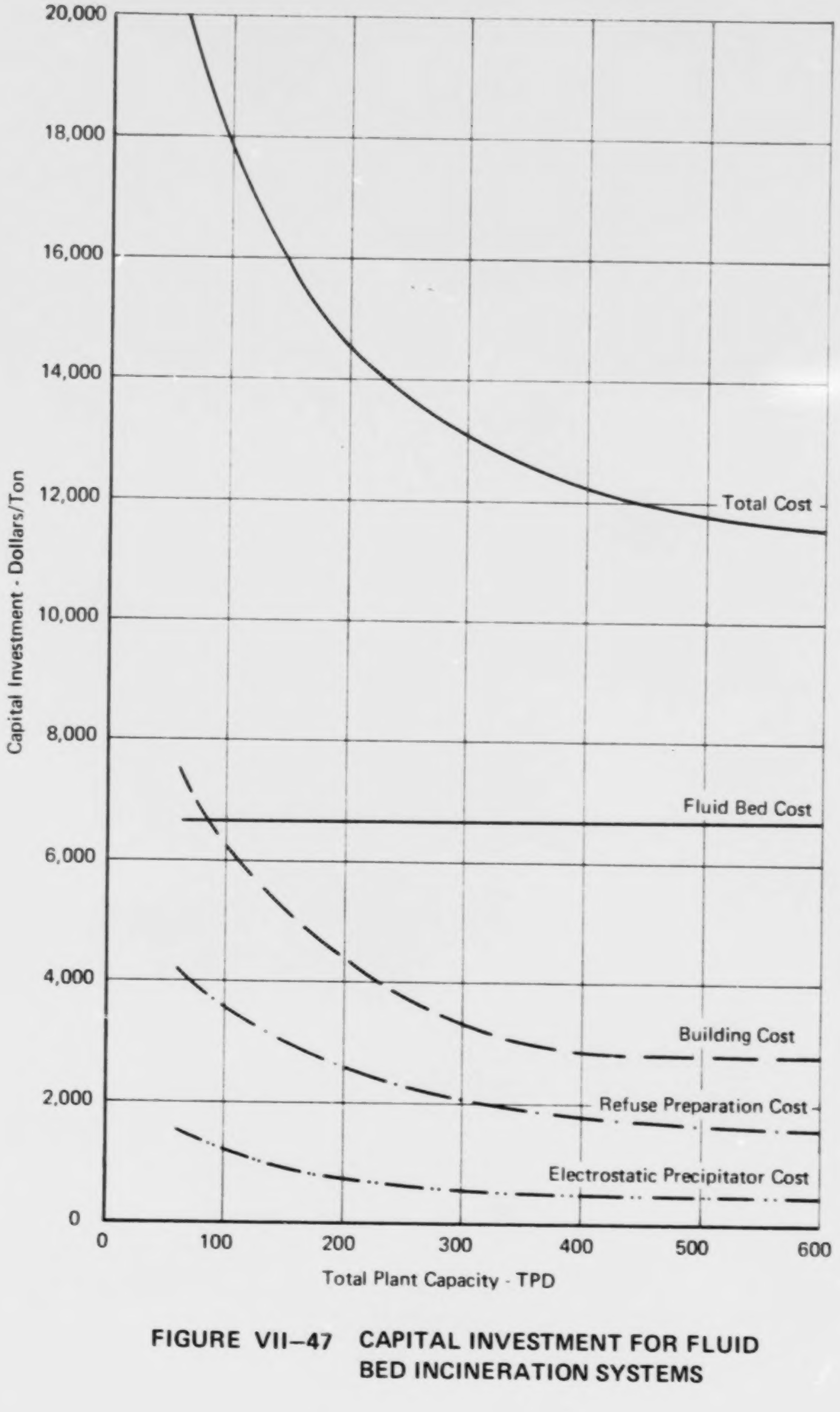


FIGURE VII–47 CAPITAL INVESTMENT FOR FLUID BED INCINERATION SYSTEMS

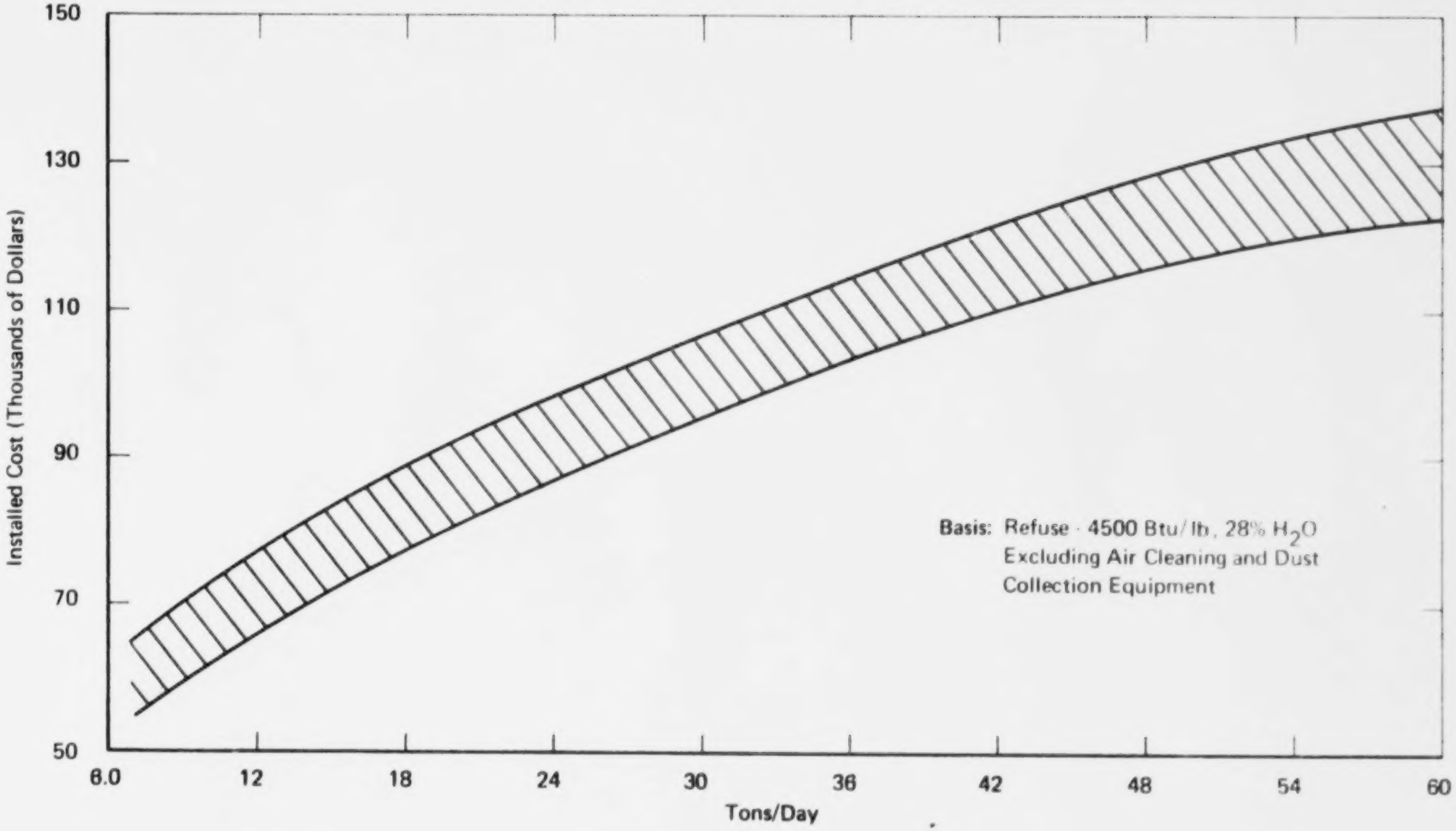


FIGURE VII–48 CAPITAL INVESTMENT FOR FLUIDIZED BED HEAT RECOVERY SYSTEMS

Direct operating labor for the incinerator proper should not exceed one man per shift for the largest units and is estimated to require only one-half of an operator's time of the 0.5 T/hour units. The major direct labor costs for fluidized bed incinerators will be in the preparation of the refuse for feeding the incinerator.

The off-gas handling system should be capable of removing dust from off-gases that are estimated to be in the vicinity of 900° to 1000°F for incinerators with heat-recovery equipment and 1600°F without heat recovery. Based on a review of the composition of the noncombustibles present in refuse, it is estimated that from one-third to one-half of these noncombustibles will be removed via the off-gases.

A sample calculation of the total operating costs is given in Table VII-43 for a 60-TPD installation. The basis for these costs is as presented in the Introduction to Chapter VII. Costs for other size installations, operating at one, two and three shifts per day, are summarized in Figure VII-49 and the distribution of costs among the various cost elements are given in Table VII-44.

Both capital and operating costs are clearly rough estimates for the application of fluid bed technology to municipal refuse incineration, an application which is yet to be demonstrated to be technically feasible. As such, these costs are tentatively high and reflect little more than the cost of such a system relative to conventional systems.

## 6. Pyrolysis of Solid Waste

### a. Introduction

The pyrolysis of carbonaceous solids is a destructive distillation process effected by the application of heat to the solid in the absence of air. The solid decomposes into gaseous, liquid, and solid products.

In general, the gaseous products contain combustible hydrocarbon; the liquid is a mixture of water, oils and tar; and the solid is a carbon-rich residue. The quality and quantity of products obtained depend upon many factors, some of the most important being the type of carbonaceous solid employed, the ultimate temperature attained, the heating rate, and the type of equipment used. Within certain limits, manipulation of these variables offers a mechanism for controlling the quality and yield of products.

Although detailed pyrolysis behavior can only be discussed in the context of a given solid material, a given pyrolysis temperature, and a given type of equipment, there are certain generalized features of the pyrolysis process that constitute basic principles as discussed below.

## TABLE VII-43

## ESTIMATED OPERATING COST FOR A FLUID BED INCINERATOR

Reference Location: Boston, Massachusetts, 1969 dollars
Plant Capacity: 60 ton/24 hr; (one unit @ 60 ton/24-hr day)
Load Factor: 250 days per year; 3 shifts per day
Annual Consumption: 15,000 tons refuse/year
Capital Investment: $1,198,000

| | Units | Dollars/Unit | Units/Ton Refuse Consumed | Dollars/Ton Refuse Consumed |
|---|---|---|---|---|
| **Variable Costs** | | | | |
| Electricity | kwh | $0.015 | 159 | 2.39 |
| Water | M gal | $0.30 | 1.3 | 0.39 |
| | | | | $2.78 |
| **Semi-Variable Costs** | | | | |
| Labor | | | | |
| 1 crane operator per shift @ $5.00/hour | | | | 2.08 |
| 1 furnace operator per shift @ $5.00/hour | | | | 2.08 |
| 1 pulping operator per shift @ $4.00/hour | | | | 1.66 |
| 1 residue man per shift @ $3.00/hour | | | | 1.25 |
| 1 supervisor @ $14,000/year | | | | 0.93 |
| 1 weigh scale operator @ $5,500/year | | | | 0.37 |
| 1 shredding system operator @ $10,000/year | | | | 0.67 |
| | | | | $9.04 |
| Overhead @ 40% of labor and supervision | | | | 3.62 |
| Maintenance and repair @ 4% of capital investment | | | | 3.19 |
| | | | | $15.85 |
| **Fixed Costs** | | | | |
| Amortization (15 years) @ 6.67% of capital investment | | | | 5.33 |
| Interest on loan @ 3% of capital investment | | | | 2.40 |
| | | | | $7.73 |
| Total Costs | | | | $26.36 |

## TABLE VII-44

## DISTRIBUTION OF TOTAL OPERATING COST FOR FLUID BED INCINERATORS

| Total Capacity | Shifts (%) | Power (%) | Water (%) | Labor and Overhead (%) | Maintenance (%) | Capital Charges (%) | Total (%) |
|---|---|---|---|---|---|---|---|
| 60 | 3 | 9 | 1 | 49 | 12 | 29 | 100 |
| 180 | 3 | 16 | 3 | 28 | 16 | 37 | 100 |
| 300 | 3 | 19 | 3 | 23 | 16 | 39 | 100 |
| 60 | 2 | 7 | 1 | 45 | 11 | 36 | 100 |
| 180 | 2 | 13 | 2 | 25 | 14 | 46 | 100 |
| 300 | 2 | 15 | 3 | 20 | 15 | 47 | 100 |
| 60 | 1 | 5 | 1 | 37 | 10 | 47 | 100 |
| 180 | 1 | 8 | 1 | 20 | 12 | 59 | 100 |
| 300 | 1 | 10 | 2 | 16 | 12 | 60 | 100 |

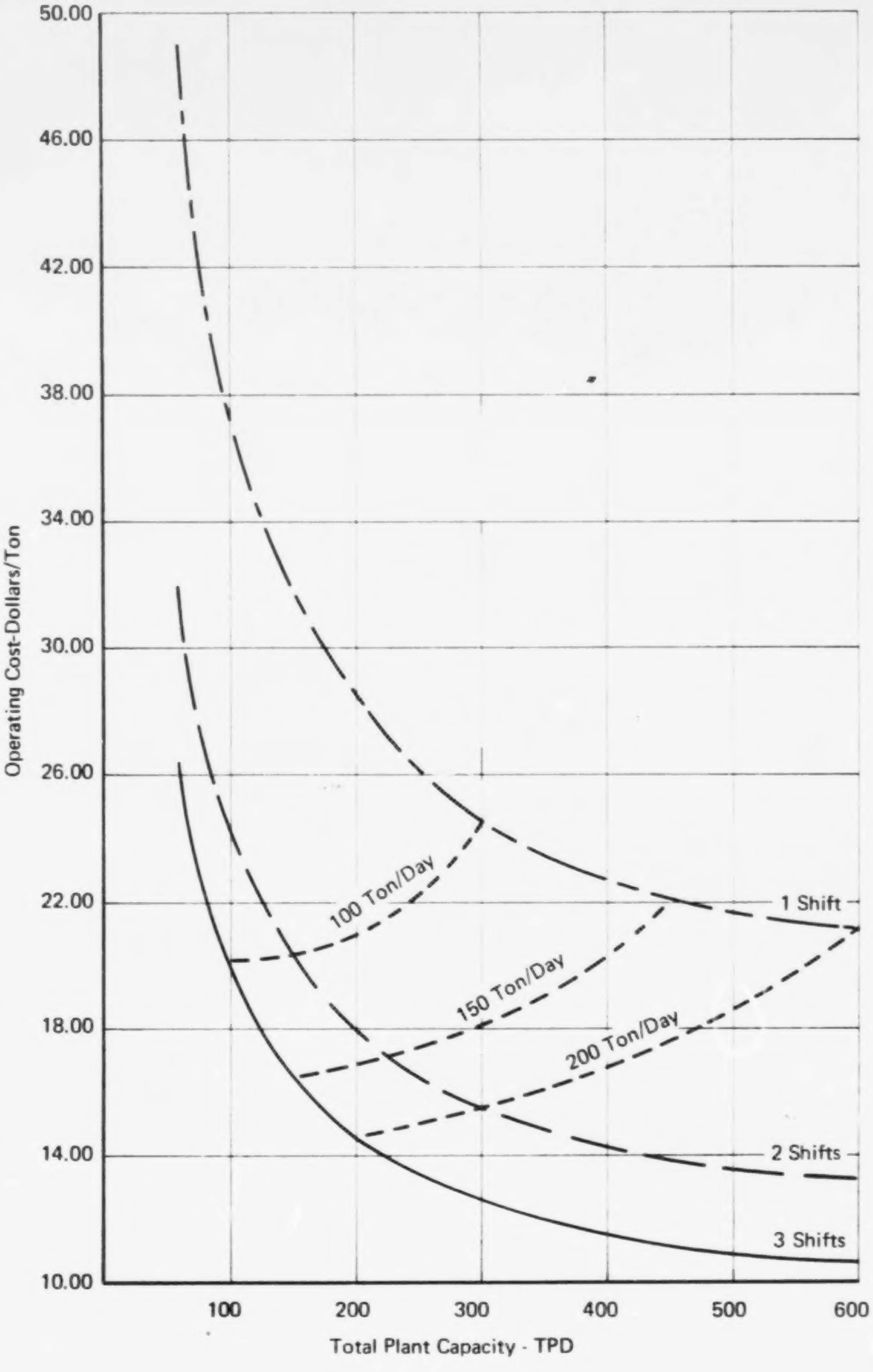


FIGURE VII–49 TOTAL OPERATING COST FOR FLUID BED INCINERATION SYSTEMS

Both chemical and physical changes occur in solids during pyrolysis. The most important physical change in materials, such as bituminous coal and some plastics, is a softening effect resulting in a plastic mass, followed by a resolidification resulting in a solid residue. Other solids, including many plastics found in refuse, simply melt and do not resolidify unless they are cooled. Cellulosic materials, such as wood and paper, increase in porosity and swell a certain amount as the volatile components are evolved. These physical changes are important because of their effect on both the handling of the material in the pyrolysis equipment and the reactivity and strength of the solid residue.

The chemical changes occurring during pyrolysis involve reactions that decompose the original material into products. Primary products are evolved directly from the complex organic molecules that are typical of organic solids. As heating proceeds the primary products further decompose or crack, forming secondary products and usually depositing solid carbon. The composition of the final products depends upon the heating rate and the ultimate temperature attained. As the ultimate temperature increases, the secondary products become simpler in structure and more hydrogen-rich in composition. At the same time the solid residue becomes more like graphitic carbon in both chemical composition and physical structure.

The temperature at which the rate of evolution of pyrolysis products becomes significant depends upon the solid being heated. In the case of wood and paper it is known that a substantial amount of weight loss occurs in pyrolysis at temperatures as low as 400°F, whereas temperatures as high as 700°F are required for a significant weight loss from coal. The behavior of solid refuse is similar to that of wood and paper.

Whether the over-all pyrolysis process of a given solid is endothermic or exothermic depends upon the ultimate temperature attained. In the case of most materials the process is endothermic at lower temperatures and exothermic at higher temperatures. Thus as the material is heated, energy is first absorbed and then released. If the ultimate temperature attained is high enough the net energy transfer will be away from the material.

The calorific value of the pyrolysis products is the sum of the calorific value of the original solids and the net energy added to the solid during pyrolysis. Therefore, in accordance with the above discussion, the calorific value of the pyrolysis products depends upon the temperature of the process. Below a certain temperature the calorific value of the pyrolysis products is higher than that of the original material. Above that same temperature, the calorific value of the original material is higher than that of the products. In the case of many carbonaceous materials the energy absorbed or liberated in pyrolysis is negligible in comparison with the calorific value of either the pyrolysis products or the original material. However, this does not appear to be the case with refuse, as is discussed later.

There is some question among researchers as to whether the rate of pyrolysis is controlled by the rate of the chemical reactions or the rate of the physical processes of heat transfer into the solid material and diffusion of the volatiles out of the solid.[58] This is an important question in practical applications of the pyrolysis process, and its answer in the case of solid refuse probably depends upon the temperature level of the process and the size of the refuse pieces. At temperatures below around 800°F or 900°F, the rates of the chemical reactions appear to be slower than the rate of heat transfer and diffusion in pieces smaller than around 0.5-inch in size. In this case the rate of pyrolysis would be limited by the rate of the chemical reactions. The temperature dependence of pyrolysis is much stronger than that of heat transfer and diffusion, and the rate of pyrolysis of pieces as small as 0.1 inch is controlled by the physical processes at temperatures above 800°F or 900°F. As the specimen size increases, the shift in rate control occurs at lower and lower temperatures. The rate of pyrolysis of pieces larger than 2 or 3 inches is probably controlled by heat transfer and diffusion at all temperatures of practical interest.

The temperature above which no further weight loss occurs by pyrolysis is a function of the material being heated. In the case of bituminous coal the weight loss achieved by pyrolysis at 1700°F is about as high as could be obtained at any higher temperature of practical interest. The limiting temperature for refuse pyrolysis would appear to be as low as 1200 or 1300°F, but this depends of course upon the composition of the refuse. If the refuse is mainly paper, as is often the case, then knowledge of the pyrolysis of cellulose,[59] which is effectively the same as paper in this context, indicates that essentially complete pyrolysis could be achieved at around 1000°F.

### b. Coal Pyrolysis

Pyrolysis has been employed for ages, having been first used for the production of charcoal from wood. A large portion of the extensive technology of pyrolysis that now exists was developed in the coal carbonization industry. A brief description of coal carbonization is given below since knowledge in that area provides a background of technology for the process of refuse pyrolysis. It is also true that many components of solid refuse exhibit several pyrolysis properties similar to those of coal. The following discussion is summarized from the detailed presentation of coal carbonization technology given by Wilson and Wells.[60]

The carbonization of coal is a pyrolysis process since it is the destructive heating of coal in the absence of air with the production of coke, and the evolution of a number of volatile products. In a Koppers-type oven, the coke remains in the retort and the volatiles escape to other parts of the equipment.

Because of its striking effect upon the products of the process, temperature is used as a basis for classifying carbonization processes. Each of two regions of carbonization temperatures is, in general, associated with a certain type of product yield. These two intervals are approximately 850°–1350°F and 1600°–2200°F, and carbonization processes conducted therein are termed low-temperature and high-temperature, respectively.

The principal products obtained in low-temperature carbonization include char or semi-coke, tar, light oils, and a gas of high heating value. The char is a free-burning, smokeless fuel, the production of which has been the chief objective of low-temperature carbonization in the United States. The char is also used as a blending agent in high-temperature carbonization. The low-temperature tar yield is relatively high and contains a wide variety of compounds.

High-temperature carbonization furnishes coke for blast furnaces and cupolas, and it has been by far the most important application of pyrolysis in the United States. The coke, along with tar, gas and light oils, is produced in by-product coke ovens. These products have been the source of hundreds of coal chemicals. Since the main objective of high-temperature carbonization has been the production of metallurgical coke, the supply of coal chemicals has depended upon the demand for coke.

Low-temperature carbonization has not been as important as high-temperature carbonization because the low-temperature process does not produce a unique product that is in strong demand. The conditions of our economy are such that the many products which may be produced from the tar and light oils are supplied by other sources. A similar condition exists in the case of gases and char. The responsible competitors are petroleum and natural gas.

The coal is usually heated in carbonization processes by burning a portion of the coal or its carbonization products. In some processes the heat for carbonization is produced by burning the volatile products and a portion of the cola, or coke, in the coking chamber in direct contact with the balance of the charge. The energy liberated by combustion is radiated downward into the charge from the dome-shaped roof of the chamber, and the products of combustion escape through a hole in the roof. Such a design, which is known as the beehive coke oven, is the oldest method now in use.

Other methods of carbonization permit recovery of the volatile products with almost no contact or dilution with combustion products and in forms which can be purified and separated into their various fractions. In these processes, which are known as by-product coke ovens or gas retorts, the charge is heated indirectly in a chamber which is closed except for an outlet for the volatiles. The fuel used for heating is a gas which can either be a portion of the gas evolved in the process or a gas from some other source. The gas is burned in flues located in the walls of the carbonization chamber, and the heat is conducted through the walls to the charge.

The two general methods of carbonization described above are usually regarded as high-temperature processes, although certain features of the schemes are employed in low-temperature processes. In general, low-temperature processes can be classified as either batch processes in which a stationary charge is carbonized in a stationary retort, or continuous processes in which the charge passes through the retort as a continuous stream.

Owing to the relatively small temperature gradient associated with the low-temperature process, the rate of heat transfer to the coal is slow and the coal must be coked in thin layers. Consequently, the capacity of batch retorts is relatively small. Also, coal changes volume during carbonization, first swelling and then shrinking, and attempts to achieve the highly desirable feature of having both sides of the thin charge contact a heating surface have included the use of either moving walls or tapering vertical retorts.

Designs of continuous retorts for low-temperature carbonization have included schemes in which thin layers of coal move through the retort, and schemes involving agitation of the coal during its passage through the retort. A design that employs both thin layers and agitation of the coal is a cylindrical drum, slightly inclined from the horizontal and rotating so as to move the coal slowly from the higher feed-end to the lower exit-end. Various arrangements of baffles are usually employed in these drums to augment movement and contact of the coal with the hot surfaces. In other designs, impellers or screws are used to move the coal through the retort. In still other designs, heated steel balls are fed into the retort with the coal in order to increase the heating rate of the coal and also to wear coke deposits from the walls.

Many carbonization processes employing various arrangements of the generalized features outlined above have been developed. High-temperature processes have been used very successfully in industry, but the status of the low-temperature processes is not so bright, partly because of technical difficulties but mainly because of economic conditions. Nevertheless it does appear that low-temperature processes could assume a position of importance if the demand for this process becomes strong enough.

### c. Current Status of Refuse Pyrolysis Technology

*(1) Process Concepts.* The process of refuse pyrolysis is a relatively new concept, the technology of which is very limited. The knowledge of this process that does exist has been generated mainly in laboratory investigations, but some information is beginning to appear from full-scale processes. The following discussion outlines the present knowledge of the process in the context of a general, idealized flow diagram of the refuse pyrolysis concept.

Various arrangements of equipment can be visualized for effecting the pyrolysis of refuse. In general, the process will employ a storage bin, a feeder, a grinder or shredder, a pyrolysis reactor fired with part or all of the volatile pyrolysis products, a particulate recovery unit, and units for collecting and storing the solid, liquid, and gaseous products. A general scheme is diagrammed in Figure VII-50.

Individual process schemes may differ in many details, such as the degree of shredding, the method of feeding refuse and the technique of product recovery. Also the amount and types of products recovered can vary between the two extremes in which either all products are recovered and separated into several components or no products are recovered. In the latter case enough air or steam is fed into the pyrolysis reactor to convert the refuse completely into combustible volatiles which may be used for power production or in some other type of energy recovery. The latter process where no condensed phase products are recovered is usually known as a gasifier instead of a pyrolyzer.

The pyrolysis reactor is a unit in which the refuse is heated to, and maintained at, the desired pyrolysis temperature. The refuse begins to pyrolyze as it is being heated, and the amount of pyrolysis occurring at temperatures below the ultimate temperature attained depends upon the heating rate. Auxiliary fuel is used for starting the process.

Heating in the reactor can be either direct or indirect. In the case of direct heating, where the heating medium contacts the refuse, a desired amount of combustion can occur in the pyrolyzer if a controlled amount of air or steam injection is employed. This controlled combustion can be used to supply the energy required in the pyrolyzer. Although the division between pyrolyzers and gasifiers is not sharp, the process appears to be known as gasification if more than a certain amount of the conversion from solid to gas occurs by chemical reaction with the ambient gas. If the heating gas is not oxidizing, then of course no combustion occurs in the pyrolyzer.

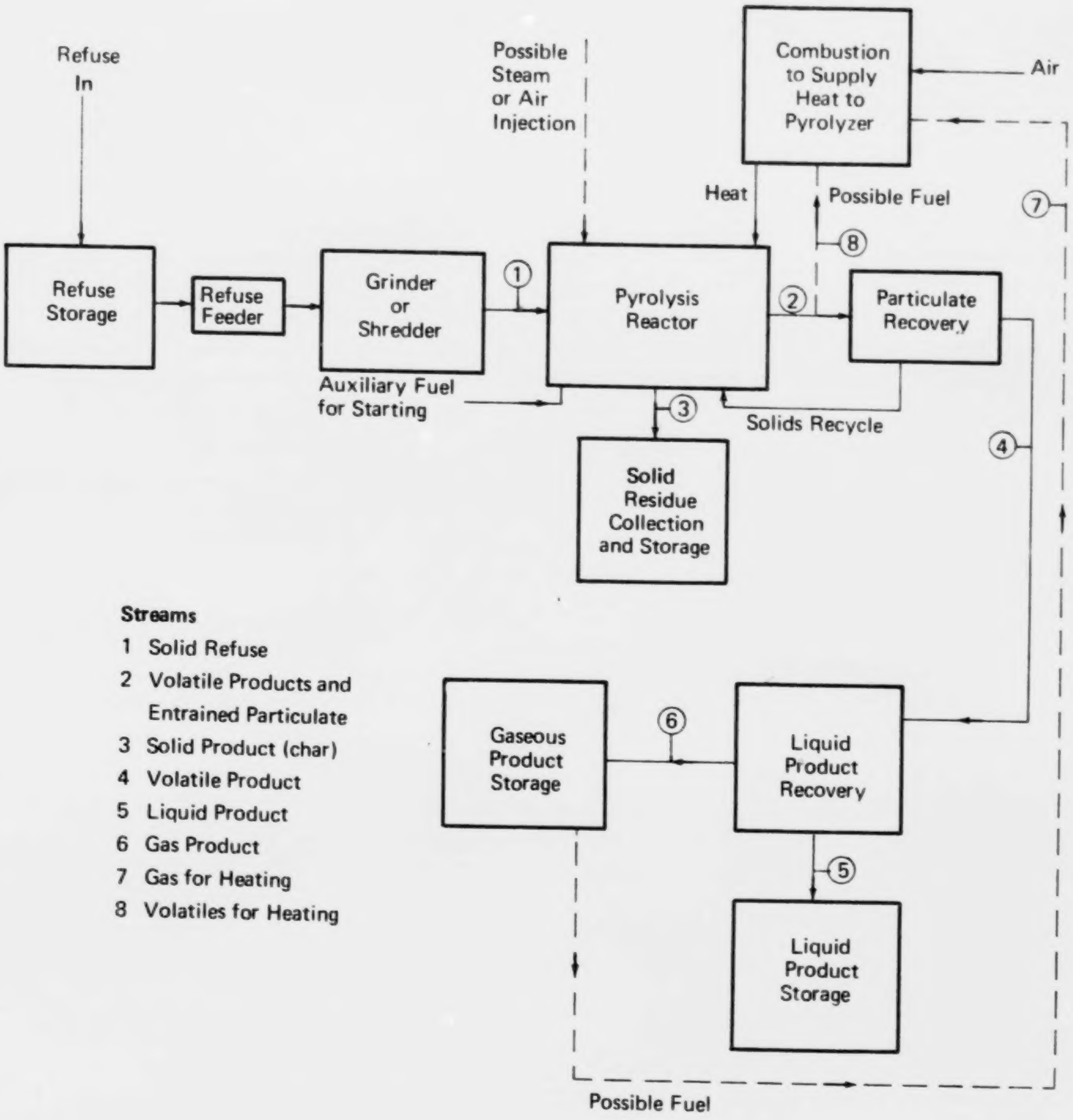

Refuse In
Refuse Storage
Refuse Feeder
Grinder or Shredder
Possible Steam or Air Injection
① 
Pyrolysis Reactor
Auxiliary Fuel for Starting
Combustion to Supply Heat to Pyrolyzer
Air
Heat
Possible Fuel
⑧
②
Particulate Recovery
⑦
③
Solids Recycle
④
Solid Residue Collection and Storage
Streams
1 Solid Refuse
2 Volatile Products and Entrained Particulate
3 Solid Product (char)
4 Volatile Product
5 Liquid Product
6 Gas Product
7 Gas for Heating
8 Volatiles for Heating
Gaseous Product Storage
⑥
Liquid Product Recovery
⑤
Liquid Product Storage
Possible Fuel

FIGURE VII–50 SCHEMATIC ARRANGEMENT OF REFUSE PYROLYSIS PROCESS

In the case of indirect heating, the pyrolyzer is heated externally and the refuse is heated by the walls of the reactor. A small amount of air may enter the pyrolyzer along with the refuse, but this entry can be maintained at a level too low to contribute a significant amount of oxidization by the use of an air seal.

Different designs for the reactor can be envisioned. One that has been used in a full-scale process is an air-tight, cylindrical retort that rotates slowly on a slight incline, and is fired externally with pyrolysis gas.[61] The refuse enters and leaves, respectively, at the higher and lower ends of the retort. The main design used in laboratory tests is a batch retort heated indirectly with electricity.[62-64] Laboratory investigators have considered the use of a fluidized bed pyrolyzer,[65] but such a unit has not yet been used for solid-refuse pyrolysis.

Shredding equipment is included in Figure VII-50 because the times required to pyrolyze large pieces of refuse appear to be prohibitively long. This point is illustrated below where the time required for pyrolysis is shown to be strongly dependent upon the size of the refuse pieces. An hour or more is required for pieces that are smaller than many of those found in typical refuse.

The particulate recovery function following the pyrolysis reactor is necessary to prevent carryover of solid material into the liquid and gaseous products. If, instead of employing product recovery, the pyrolysis products are burned, particle recovery would still be necessary to prevent particulate emission to the atmosphere and damage to certain types of energy-recovery or power-generating equipment. In any event, the collected solids can be recycled to the reactor since such material will probably be only incompletely pyrolyzed. The amount of solids escaping from the reactor in the product stream will depend upon both the composition and particle size of the refuse and the design of the reactor.

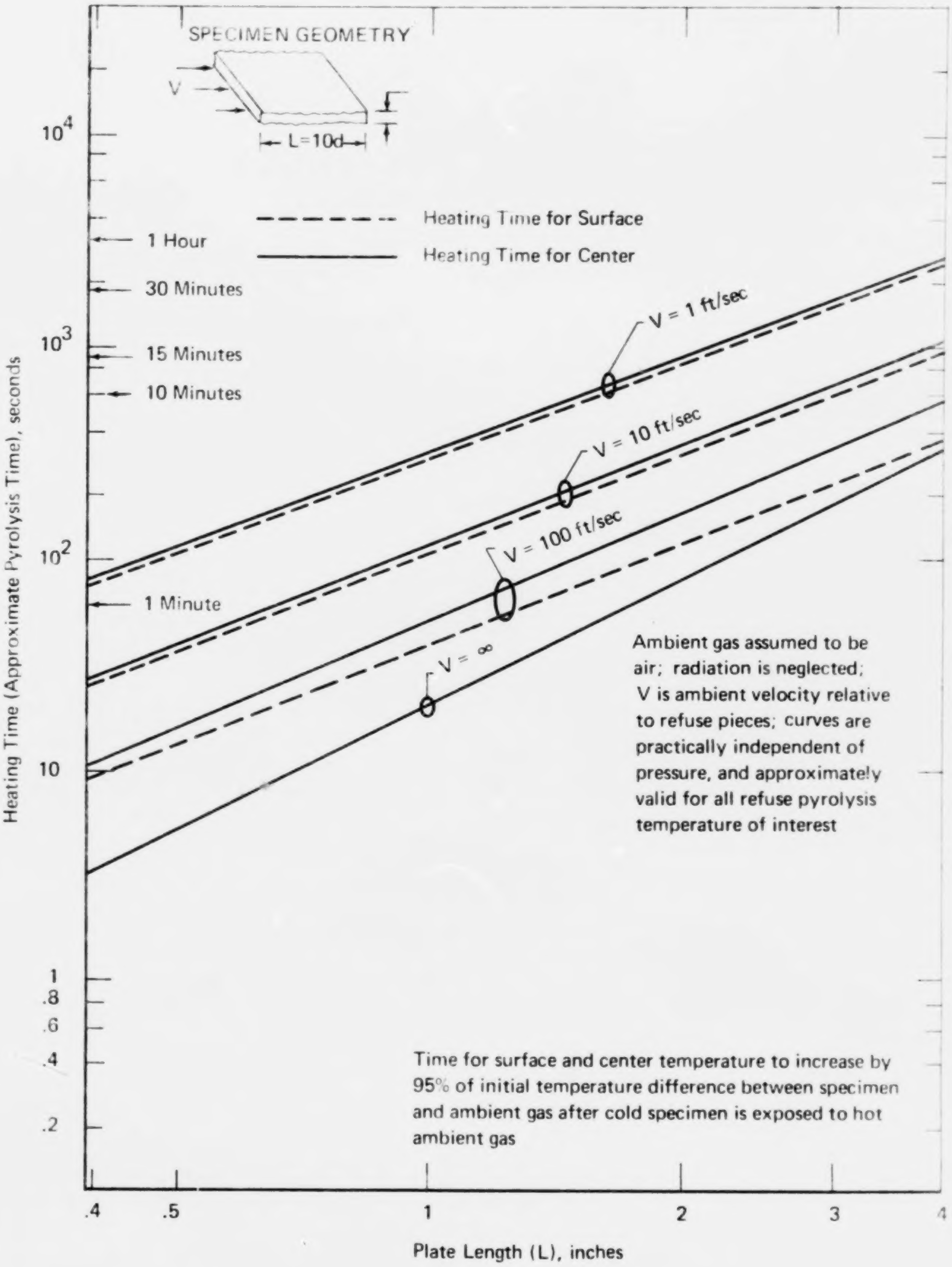
*(2) The Pyrolysis Process.* The time required for pyrolysis is estimated here by assuming that the rate of pyrolysis is controlled by the rate of heating the individual refuse pieces. Since the rate of the pyrolysis reaction is fast compared with the heating rate for the temperatures and specimen sizes of interest in refuse pyrolysis, most materials in refuse, such as paper, garbage, and wood, heat internally at a slow enough rate so that pyrolysis at a given temperature essentially occurs instantaneously when the refuse reaches that temperature. Therefore the time required for pyrolysis is the time required for heating.

The prediction of heating (pyrolysis) rates for refuse in thin beds is a problem in unsteady heat transfer, complicated by both endothermic and exothermic reactions. The time is estimated here by considering simplified but still meaningful conditions. Energy absorption and generation by the pyrolysis reaction is neglected, and the refuse is assumed to be suddenly plunged into a hot, well-mixed pyrolysis chamber maintained at constant temperature. Heat transfer by radiation and by particle-particle contact is neglected. Furthermore, the refuse pieces are assumed to be either thin, flat slabs or spheres, the heating times of which should bracket the times for actual shapes.

The heating time is defined as the time required for the center temperature or the surface temperature of a specimen to rise by 95% of the initial temperature difference between the specimen and the surroundings. The heating time is calculated using the solution of the differential equation describing the heat transfer process, which is given in graphical form in the literature.[66] The thermal diffusivity of refuse is assumed to be $3.9 \times 10^{-3}$ sq ft/hr, which is roughly that of paper, wood, coal and many other carbonaceous solids. The thermal properties of the ambient gas are assumed to be those of air. The calculation is approximately valid at all temperatures of interest in refuse pyrolysis.

The estimated pyrolysis times are given in Figures VII-51 and VII-52 for different values of specimen size and relative velocity between the refuse pieces and the ambient gas. The effect of specimen size is found to be very significant, thus showing the importance of size reduction. For example, if the relative velocity is 1 ft/sec, the heating time for the center of a sphere drops from about 75 minutes to about 20 minutes when the diameter is reduced from 2 inches to 1 inch. Under the same conditions, the heating time for a flat plate with a thickness of 1/10 of its length falls from about 40 minutes to about 5 minutes when the length is reduced from 4 inches to 1 inch. The effect of gas velocity is also important, thus showing that it is desirable to promote relative motion between the gas and the refuse. Relative velocities larger than around 10 ft/sec are probably of little practical interest although they are considered here. The curves labeled $V = \infty$ represent an infinitely large surface heat-transfer coefficient, which is equivalent to either an infinite relative velocity or an unlimited contribution from radiation and particle-particle contact. Under such conditions the surface of the specimen attains the temperature of the pyrolysis chamber immediately upon entering the chamber, and the rate of heating is determined solely by the thermal properties of the refuse.

In applying the information in Figures VII-51 and VII-52 to the actual process of refuse pyrolysis, the information on plates (Figure VII-51) should be roughly applicable to thin pieces and the behavior of spheres (Figure VII-52) should roughly simulate the behavior of material in the form of chunks. Since the conditions assumed in the calculation generally favor rapid heating and pyrolysis, the results may be regarded as underestimations, with the actual pyrolysis times being larger than the times found here. Generally speaking, it appears that the refuse should be reduced to sizes less than about 4 inches for plates and less than about 2 inches for chunks, if the required residence time in the pyrolyzer is to be less than 45 minutes to 1 hour. If the refuse contains pieces larger than that, then using a pyrolyzer with residence times less than those indicated above, without



Ambient gas assumed to be air; radiation is neglected; V is ambient velocity relative to refuse pieces; curves are practically independent of pressure, and approximately valid for all refuse pyrolysis temperature of interest

Time for surface and center temperature to increase by 95% of initial temperature difference between specimen and ambient gas after cold specimen is exposed to hot ambient gas

FIGURE VII–51 TIME REQUIRED TO PYROLYZE FLAT REFUSE PIECES

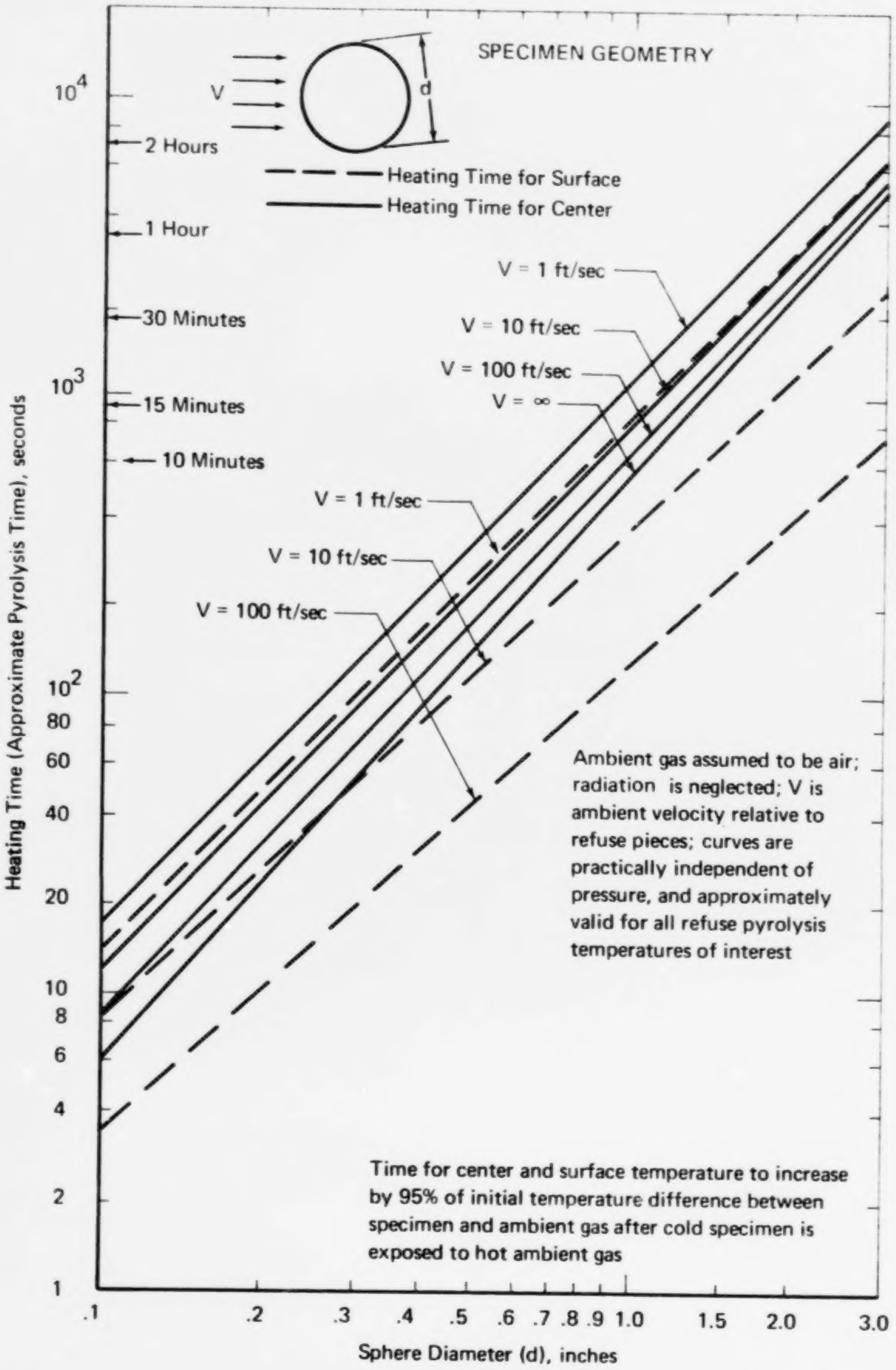


FIGURE VII–52 TIME REQUIRED TO PYROLYZE SPHERICAL REFUSE PIECES

shredding or some type of size reduction, would result in an incompletely pyrolyzed solid residue. Such operation would tend to defeat the purpose of the pyrolysis scheme.

*(3) Pyrolysis Products*

*(a) Liquid Products.* The liquid product of refuse pyrolysis is known to contain an incompletely described mixture of alcohols, oils and tars known as pyroligneous acids. Chromatography and infrared spectroscopy are being employed in analyzing this liquid.[63] It is known that the liquid fraction distilled from typical refuse is a highly complex mixture of many organic compounds, containing from 70 to 80% water, the remainder being various alcohols, ketones, tars, acetic acid, and other organics.[63] Methanol, 2-methyl-1-propanol, 1-pentanol, 3-pentanol, 1,3-propanediol, 1-hexanol, and acetic acid have been separated and tentatively identified.[67]

It appears from the information in Table VII-45 that the yield of liquid product is highly dependent upon the refuse composition. Furthermore, Tables VII-46 and VII-47 indicate that the liquid yield depends upon both the heating rate and the ultimate temperature attained. The yield of liquid, expressed as a percentage of the refuse combustibles (air-dried, ash-free basis), is found to be around 50% or 60% (Tables VII-45 and VII-46), roughly half of which is water. The yield decreases with increasing temperature (Table VII-46) and, if judged on the behavior of newspaper (Table VII-47), the yield generally increases as the heating rate increases. The calorific value of the liquid is found to decrease from about 2000 to about 1000 Btu/lb of refuse combustibles as the temperature of pyrolysis increases from 900°F to 1700°F.[63]

*(b) Gaseous Products.* The yield as well as the calorific value of the gaseous products of refuse pyrolysis depend upon the type of refuse and the temperature and heating rate employed in the pyrolyzer. The yield for the different components shown in Table VII-45 varies from about 17% to about 31% of the weight of the air-dried refuse. The mean gas yield at around 1500°F is about 25% by weight of the air-dried, ash-free refuse. Table VII-46 indicates that the yield approximately doubles when the pyrolysis temperature is raised from 900°F to 1700°F. Table VII-47 indicates that the yield decreases at first and then increases as the heating rate increases over the range of heating rates shown.

As the temperature of pyrolysis increases, the total heating value (Btu/lb refuse) of the pyrolysis gases increases, but the calorific value (Btu/cu ft) does not show a regular variation according to the limited data available (see Table VII-48). Table VII-49 shows that the gases become richer in hydrogen and leaner in carbon dioxide as temperature increases. If once again we assume that newspaper is representative of refuse, then Table VII-47 indicates that the heating value of the gases first decreases and then increases as the heating rate is increased.

## TABLE VII-45

## YIELDS OF PYROLYSIS PRODUCTS FROM DIFFERENT REFUSE COMPONENTS
WEIGHT PERCENT OF REFUSE
(from ref. 62)*

| Component | Gas | Water | Other Liquid | Char (ash-free) | Ash |
|---|---|---|---|---|---|
| Cord hardwood | 17.30 | 31.93 | 20.80 | 29.54 | 0.43 |
| Rubber | 17.29 | 3.91 | 42.45 | 27.50 | 8.85 |
| White pine sawdust | 20.41 | 32.78 | 24.50 | 22.17 | 0.14 |
| Balsam spruce | 29.98 | 21.03 | 28.61 | 17.31 | 3.07 |
| Hardwood leaf mixture | 22.29 | 31.87 | 12.27 | 29.75 | 3.82 |
| Newspaper I | 25.82 | 33.92 | 10.15 | 28.68 | 1.43 |
| II | 29.30 | 31.36 | 10.80 | 27.11 | 1.43 |
| Corrugated box paper | 26.32 | 35.93 | 5.79 | 26.90 | 5.06 |
| Brown paper | 20.89 | 43.10 | 2.88 | 32.12 | 1.01 |
| Magazine paper I | 19.53 | 25.94 | 10.84 | 21.22 | 22.47 |
| II | 21.96 | 25.91 | 10.17 | 19.49 | 22.47 |
| Lawn grass | 26.15 | 24.73 | 11.46 | 31.47 | 6.19 |
| Citrus fruit waste | 31.21 | 29.99 | 17.50 | 18.12 | 3.18 |
| Vegetable food waste | 27.55 | 27.15 | 20.24 | 20.17 | 4.89 |
| Mean Values | 24.25 | 23.50 | 22.67 | 24.72 | 11.30 |

*Refuse was shredded, air-dried, and pyrolyzed in a retort at 1500°F.

## TABLE VII-46

## YIELDS OF PYROLYSIS PRODUCTS FROM REFUSE AT DIFFERENT TEMPERATURES
PERCENT BY WEIGHT OF REFUSE COMBUSTIBLES
(from ref. 63)

| Temperature °F | Gases | Liquid (including water) | Char |
|---|---|---|---|
| 900 | 12.33 | 61.08 | 24.71 |
| 1200 | 18.64 | 59.18 | 21.80 |
| 1500 | 23.69 | 59.67 | 17.24 |
| 1700 | 24.36 | 58.70 | 17.67 |

## TABLE VII-47

## EFFECT OF HEATING RATE ON YIELDS OF PYROLYSIS PRODUCTS AND HEATING VALUE OF THE PYROLYSIS GAS FROM NEWSPAPER

(from ref. 62)

| Time taken to heat to 1500°F, minutes | Yield, weight percent of air-dried refuse | | | | Heating value of gas, Btu/lb of newspaper |
|---|---|---|---|---|---|
| | Gas | Water | Other Liquid | Char (ash-free) | |
| 1 | 36.35 | 24.08 | 19.14 | 19.10 | 2,045 |
| 6 | 27.11 | 27.35 | 25.55 | 18.56 | 1,425 |
| 10 | 24.80 | 27.41 | 25.70 | 20.66 | 1,207 |
| 21 | 23.48 | 28.23 | 26.23 | 20.63 | 1,092 |
| 30 | 24.30 | 27.93 | 24.48 | 21.86 | 1,192 |
| 40 | 24.15 | 27.13 | 24.75 | 22.54 | 1,129 |
| 60 | 25.26 | 33.23 | 12.00 | 28.08 | 1,330 |
| 60 | 29.85 | 30.73 | 9.93 | 28.06 | 1,730 |
| 71 | 31.10 | 28.28 | 10.67 | 28.52 | 1,568 |

## TABLE VII-48

## CALORIFIC VALUE OF PYROLYSIS GASES OBTAINED BY PYROLIZING REFUSE AT DIFFERENT TEMPERATURES

(from ref. 63)

| Temperature °F | Gas Yield Per Lb. of Refuse Combustibles, Cu. Ft. | Calorific Value | |
|---|---|---|---|
| | | Btu/cu. ft. Gas | Btu/lb Refuse Combustibles |
| 900 | 1.90 | 300 | 569 |
| 1200 | 2.78 | 376 | 1045 |
| 1500 | 3.62 | 344 | 1245 |
| 1700 | 3.39 | 351 | 1190 |

## TABLE VII-49

## COMPOSITION OF PYROLYSIS GASES OBTAINED BY PYROLIZING REFUSE TO DIFFERENT TEMPERATURES

(from ref. 63)

| Temperature °F | Gas Composition, % by Volume | | | | | |
|---|---|---|---|---|---|---|
| | $H_2$ | $CH_4$ | CO | $CO_2$ | $C_2H_4$ | $C_2H_6$ |
| 900 | 5.56 | 12.43 | 33.50 | 44.77 | 0.45 | 3.03 |
| 1200 | 16.58 | 15.91 | 30.49 | 31.78 | 2.18 | 3.06 |
| 1500 | 28.55 | 13.73 | 34.12 | 20.59 | 2.24 | 0.77 |
| 1700 | 32.48 | 10.45 | 35.25 | 18.31 | 2.43 | 1.07 |

In general, it appears that pyrolysis of 1 pound of refuse combustibles yields 2 to 3 cubic feet of gas, having a calorific value of around 340 Btu/cu ft. This is about one-third of the calorific value of natural gas.

*(c) Solid Products.* The solid product or char resulting from refuse (metal and glass removed) pyrolysis is an impure carbon very similar in proximate analysis to coal, the rank of which depends upon the temperature at which the refuse is pyrolyzed. If pyrolysis is conducted at 900°F, the char is similar to certain bituminous coals, whereas pyrolysis at 1700°F yields a char more like anthracite (see Table VII-50). Since the proximate analysis test for volatile matter is performed at 950°C (1742°F), which is approximately equal to the highest pyrolysis temperature (1700°F) reported in Table VII-50, it is not clear why the char resulting from that 1700°F process exhibited such a high volatile matter content. The implication is that the pyrolysis experiments reported in Table VII-50 may not have been carried to completion, since complete pyrolysis at 1700°F would be expected to eliminate essentially all of the volatile matter. However, until more data are available, the comparison between refuse chars and different coals should be a useful approximation.

The yield of char, expressed on an ash-free basis, appears to be between about 17% and 32% of the air-dried refuse, the variation resulting from different refuse compositions (see Table VII-50). The mean yield is about 17 to 25% by weight of the air-dried, ash-free refuse (see Tables VII-50 and VII-46). The yield decreases with both increasing heating rate and increasing pyrolysis temperature. It is probably safe to say that the yield decreases as the size of the refuse pieces decreases, but data have not been found to test this point.

The calorific value of the char is around 11,000 or 12,000 Btu/lb of air-dried char and appears to decrease slowly as pyrolysis temperature increases (see Table VII-50). The calorific value undoubtedly depends also on heating rate and refuse composition, but data illustrating this dependence do not appear to be available.

The composition of the char depends upon the composition of the refuse, and this probably causes differences in data reported in the literature. The ash content of the char shown in Table VII-49 appears to be lower than that of typical refuse. Based on the literature, the composition of "typical" refuse is approximately 28% moisture, 43% volatile matter, 7% fixed carbon, and 22% ash. On this basis the ash content of completely devolatilized, dry char would be around 76%. If only half of the volatile matter is evolved during pyrolysis, then the ash content of the dry char would be 56%. Therefore, if one assumes that at least half of the volatile matter is evolved during pyrolysis, the ash content of the char from typical refuse probably has an ash content of over 50% or 60%. Since

## TABLE VII-50

## COMPARISON OF CHAR PRODUCED BY REFUSE PYROLYSIS WITH CERTAIN COALS

| Proximate Analysis of Air-Dried Material | Bituminous Coal from Lower Freeport Seam[60] | Char Resulting from Refuse Pyrolysis at Different Temperatures[63] | | | | Pennsylvania Anthracite |
|---|---|---|---|---|---|---|
| | | 900°F | 1200°F | 1500°F | 1700°F | |
| Volatile matter % | 23.84 | 21.81 | 15.05 | 8.13 | 8.30 | 8.47 |
| Fixed carbon % | 65.36 | 70.48 | 70.67 | 79.05 | 77.23 | 76.65 |
| Ash % | 8.61 | 7.71 | 14.28 | 12.82 | 14.47 | 11.50 |
| Btu/lb of air-dried material | 14,188 | 12,120 | 12,280 | 11,540 | 11,400 | 13.617 |

this is a rather high ash content, it will be desirable to remove some of the ash forming-material, such as glass, metal and other inert objects, prior to pyrolysis, in order to improve the quality of the char.

*(4) Energy Balances for Pyrolysis Concepts.* The yields and calorific values of the pyrolysis products presented above permit discussion of the method of heating the reactor. Figure VII-51 shows the heating fuel coming from the product stream before any separation of the volatile products occurs. Since it has been stated[61] that the gas stream, or even a part of the gas stream, is sufficient for heating certain types of refuse, a heating fuel taken from the product stream after the liquid component has been removed is shown by a dotted line in Figure VII-51. However, the latter scheme may not provide enough fuel in some cases, so another scheme is shown in Figure VII-51 in which the heating fuel is taken from the volatiles stream before the liquid product is removed.

According to the information presented above, pyrolysis of 1 pound of metal and glass-free, air-dried refuse at around 1500°F typically yields 2 to 3 cubic feet of gas with a calorific value of about 340 Btu/cu ft about 0.55 pound of liquid product (including condensed water) with a heating value of about 2700 Btu/lb, and about 0.21 pound of char with a calorific value of about 11,500 Btu/lb dry char. Therefore, the heating values of the gas, liquid, and char are about 850, 1500, and 2420 Btu, respectively, all on a basis of 1 pound of air-dried, ash-free refuse. On the assumption that the refuse contains 22% ash, the heating values of the products on a basis of 1 pound of air-dried refuse are 660 Btu for the gas, 1170 Btu for the liquid, and 1890 Btu for the char. Since the specific heat of refuse is about 1 Btu/lb-°F,[63] the sensible energy required to heat the refuse to 1500°F is about 1430 Btu. Therefore, if we neglect the energy liberated or absorbed by the pyrolysis reaction and assume that the thermal efficiency of the pyrolysis chamber is 100%, all of the gas and part of either the liquid product or the char would be required to heat the process. However, there appears to be enough energy liberated by the pyrolysis reaction to the reduce the amount of fuel requirement to a value that even a fraction of the gas could supply, as described below.

The energy liberated by the pyrolysis reaction is the difference between the heating value of the original refuse and the total heating value of the pyrolysis products. From the above discussion the total heating value of the products is about 3700 Btu/lb air-dried refuse, and the heating value of refuse is generally around 6200 Btu/lb air-dried refuse.[64] Consequently, the energy liberated by pyrolysis appears to be 2500 Btu/lb air-dried refuse, which is large compared with the energy required for heating. This value is a rough estimation, and it may be too high since the pyrolysis energy of wood and coal has been found to be small compared with the heating value of either the original material or the pyrolysis products.[68,69] However, the accuracy of this analysis is good enough to permit the conclusion that the pyrolysis process may be energetically self-sustaining once it is started. The pyrolysis reaction can therefore be regarded as a significant source of heat, and at most only a fraction of the pyrolysis gas should be required as fuel.

Certain types of refuse will undoubtedly constitute exceptions to the above conclusion. In any case it should be possible to generate enough energy from the refuse itself to affect the pyrolysis process. This could be achieved by a combination of air or steam injection into the pyrolysis chamber and cumbustion of the volatiles. This injection, which is indicated by a dotted line in Figure VII-50, could be controlled so as to burn enough of the solid material to provide the balance of the energy requirement.

### d. Evaluation of the Process of Refuse Pyrolysis

The pyrolysis of refuse is new enough that evaluating its advantages and disadvantages is somewhat difficult owing to the lack of information. This is especially true with respect to economics. However, some preliminary speculation based on the general features of the process is useful.

Four main advantages of the process are often given:[61,63]

1. The process should facilitate the control of air pollution;
2. Useful products might be produced from the refuse;
3. The reduction in the volume of the refuse and the production of a sterile material would extend the life and improve the quality of sanitary landfills relative to untreated refuse; and
4. The process is self-sustaining with respect to energy.

The basis of the first advantage is that the process is completely contained, and it can be conducted with temperatures and oxygen concentrations much less than those existing in most incinerators. Since the process is contained, any pollutants generated therein can be collected. The relatively low temperature and oxygen concentration within the pyrolyzer suggest that the generation of oxides of nitrogen in the pyrolysis chamber will be low. However, if the volatiles were used to supply heat for pyrolysis, then this secondary combustion would presumably involve temperatures and oxygen concentrations typical of gas flames, thus reducing somewhat the advantage of the overall process with respect to reducing the generation of nitrogen oxides.

The relatively low gas velocities and volumetric rates of generation of pyrolysis gases should result in a very low level of particulate carryover. Removal of particulate from these gases can probably be most easily performed after combustion, as condensible components would probably foul particulate removal systems. The gas volumes and required efficiencies would be very much lower than for particulate removal for conventional systems.

A second, and possibly more important consideration regarding improved air pollution performance, is based on the physical transformations effected in the pyrolyzer. Raw refuse is a heterogeneous, variable, unstorable, bulky, hard-to-handle fuel requiring special combustion devices. Pyrolysis products, with minor blending, are homogeneous, consistent, storable, compact, easy-to-handle fuels, probably readily combustible in conventional furnaces with conventional burners. The effects of such a transformation on the ability to burn these materials with a minimum of air pollution are obvious and most encouraging.

The magnitude of the advantage of producing useful products from refuse depends upon economic factors that will not be analyzed here. Analysis of this advantage is difficult, not only because the exact nature of the products is not well understood but also because, as discussed earlier, it is not yet clear how much of the liquid and gas will be available after supplying process fuel. It should be remembered that the products of refuse pyrolysis are similar to the products of low-temperature coal carbonization, and that the latter process has not enjoyed a position of importance mainly because its products are produced at a lower cost by other processes involving petroleum and natural gas. However, it is true that the feed for refuse pyrolysis is readily available at negative cost near large urban centers where the products would be used,[62] an advantage that low-temperature coal carbonization never experienced. Furthermore, the fact that domestic reserves of petroleum and natural gas are decreasing adds some interest to refuse as a source of energy.

The advantage concerned with volume reduction and improved quality of material for sanitary landfilling would appear to be a costly, short-range advantage and one which is ineffective in comparison to conventional incineration. Volume reduction[63] of the combustible portion of refuse is around 50%. Since the noncombustible (metal and glass) fraction of refuse will not change volume appreciably, the total volume reduction will be somewhat less than 50%. Therefore pyrolysis would extend the life of landfills by less than a factor of 2. Since the acreages required near large urban centers for sanitary landfilling are already regarded as inadequate,[62] it appears that the above improvement leaves much to be desired with regard to long-range solutions of the solid waste problem.

The fourth advantage mentioned above – that the pyrolysis process is energetically self-sustaining – means, of course, that process fuel will not be a charge. In designing the process, the freedom in choosing both the amount of air or steam injection in the pyrolysis chamber and the point at which the volatiles stream is tapped for process fuel offers considerable freedom in selecting the fractions of solid, liquid, and gaseous products to be used as fuel, and the fractions to be produced for sale. Since other heating fuels might be available, and since the market value of some of the products may exceed their value as fuels, it may be desirable in some cases not to strive for an energetically self-sustaining process. In comparing pyrolysis with incineration, it should be noted that being energetically self-sustaining is not a unique quality.

From the point of view of process design, refuse pyrolysis is similar in many respects to low-temperature coal carbonization. The temperature at which the latter process is conducted (850-1350°F) would appear to be approximately the desirable range for refuse pyrolysis. The temperatures employed in high-temperature carbonization (1600-2200°F), which are necessary for producing metallurgical coke, appear to offer little advantage in refuse pyrolysis. Also, the products of refuse pyrolysis are quite similar to the products obtained in low-temperature coal carbonization. Consequently, the following discussion of some advantages and disadvantages already identified with respect to the design of low-temperature carbonization equipment should be relevant in the evaluation of the refuse pyrolysis process.

The low-temperature process offers the advantages of reduced capital investment resulting from the substitution of steel for refractory brickwork in the retort walls and reduced operating costs because less heat is required to raise the charge to the lower pyrolysis temperatures. In the case of coal, these potential advantages are offset by the difficulties encountered in handling and heating the coal charge at the lower temperatures. However, not all of these disadvantages should be experienced in the case of refuse. The disadvantages occur because (1) heat transfer to the coal is more difficult at the lower temperatures where the temperature gradient between the retort walls and the coal is relatively low, (2) the coal becomes plastic and swells, and thus becomes difficult to manage in a large part of the temperature range employed in the low-temperature process, and (3) the steel in the low-temperature retorts contacts hot coal, char, or tar, thereby absorbing carbon and thus warping and changing its properties. The second difficulty mentioned above would not be expected to occur in the case of refuse pyrolysis. However, with regard to the third disadvantage, it may be found that hot pyroligneous acids and other products of refuse pyrolysis are even more damaging to steel than are hot coal and its pyrolysis products. This would be especially true in the case of refuse that includes certain plastics, such as those containing chlorine and fluorine. The problem of a low rate of heat transfer would probably be as serious in refuse pyrolysis as it is in coal carbonization.

Two other problems encountered in the development of rotating cylindrical retorts for coal pyrolysis were the accumulation of coke deposits on the walls and other moving parts and the breakdown in the coke structure as a result of movement in the retort. The first type of problem may be serious in the pyrolysis of refuse containing plastics that tend to melt upon heating. The impact of the second type of problem would depend upon how the char is to be used. It would not be serious if the char is to be used as pulverized fuel or briquetted for domestic use. However, the generation of fines in the retort would aggravate the problem of particle removal from the volatiles stream if all of the volatiles are not used in heating the retort.

After looking at numerous advantages and disadvantages of the process of refuse pyrolysis, and after considering the existing knowledge of the process, it appears fairly certain from a technical point of view that such a process could probably be designed, built, and operated to handle municipal refuse. However, experience with a large-scale unit, and therefore cost information, is not available. Therefore the potential of the process appears to depend upon economic questions yet to be answered.

### e. Proposed Refuse Pyrolysis Systems

The Lantz converter,[4] a refuse pyrolysis system developed by Pan American Resources (PAR) of Albuquerque, is comprised of a sealed, air-tight retort cylinder inside a heavy insulated jacket. The retort is gas-fired, usually about 20 feet long, and revolves slowly on a slight decline from infeed to outfeed. Refuse is admitted through a seal that intermittently opens in such a way that the entry of air is minimized. The retort pyrolyzes refuse at temperatures ranging from 900°F to 1500°F, depending upon the type of refuse. The pyrolysis products appear to be similar to those discussed earlier.

One full-scale Lantz converter was installed and operated by PAR at a Ford Motor Company plant in San Jose, California, and was scheduled to begin operation[61] in 1968. This unit is reportedly designed to handle 40 to 50 TPD of plant refuse, consisting mainly of paper, wood and other packaging materials, paint sludge, and some plastics. Tests indicated that the pyrolysis scheme would work successfully on this refuse. Operation of the system has been discontinued at the plant.

Another system proposed for refuse pyrolysis is the Herreshoff continuous carbonizer built by Nichols Engineering and Research Corporation. This application of the Herreshoff furnace concept is similar to that used for sewage sludge disposal. It produces a uniform char in high yield, and is said to be readily controlled. The feed material is carefully sized to yield a granular char suitable without subsequent treatment for briquetting. Heat control is accomplished by controlled introduction of air. The off-gas in the furnace is combustible and may be used to produce plant steam or to dry the incoming feed.

The manufacturer of the Herreshoff system claims that it works well with refuse. The composition of the gas generated by the system compares well with laboratory data such as those presented earlier. It is not known whether a full-scale version on this system has actually been installed, however.

### f. Economics

The capital costs for pyrolysis furnaces should be similar to those of conventional incineration furnaces. Buildings, feed, and char handling should also be equivalent to the comparable components of conventional systems.

Differences will arise in the feed preparation and air pollution control equipment costs. Feed preparation system costs will reflect the amount of separation of glass and metals and the degree of shredding required in the system. The costs given for size reduction (Appendix II.A) for a 2-inch top-size should be a good indication of these additional costs relative to conventional incineration.

The very low pyrolysis gas velocities and volumetric rates in pyrolysis furnaces should result in a very low level of ash carryover. Complete combustion of the volatile components for heating the converter should be accomplished without the formation of soot. Consequently, it may be possible to eliminate the air pollution control cost almost completely (as given in Section VII.B).

Similarly, the system operating costs will reflect the principal differences between this approach and conventional incineration: those of size reduction and air pollution control, as discussed above.

It is not expected that any useful chemical products can be economically separated from the liquid and gaseous products of refuse pyrolysis. Instead, a portion of the products would be burned to supply the energy required to support the pyrolysis reaction; any excess could be flared (perhaps used to supply plant steam, if available in sufficient supply or marketed as a low sulfur fuel). Other potentially useful products include those components such as metals and glass removed prior to pyrolysis. The value of all of these products is uncertain and will depend heavily upon local markets. In addition, the value of the char will depend upon the ash content and degree of sterility of the material. Char markets have been suggested to include charcoal briquettes and, perhaps, moderately activated chars for some water or fume treatment applications.

### g. Required Research

The yield of products from different types of refuse pyrolyzed at different temperatures and at different heating rates seems to be fairly well understood. Also, the composition of the gases is quite well known for a range of conditions. However, research is needed to determine the kinetic parameters of the pyrolysis reaction in order to predict the residence times required in the pyrolyzer; the nature and possible uses of the products must also be studied. Furthermore the handling properties of these products should be evaluated to determine what kind of equipment is needed to collect the products and prepare them for sale.

The question of supplying energy to the pyrolyzer should be studied to determine how much of the volatile products would be consumed as fuel within the process. The effect of air and steam injection into the pyrolyzer on the quantity and quality of volatile products should be studied. Detailed points that will have to be studied in answering these questions include the heating value of the liquid product, the net energy evolved or generated by pyrolysis at different temperatures and heating rates, and the combustion properties of the pyrolyzing solids in limited air or steam.

Probably the most serious need for research is on the pilot plant scale. It appears that sufficient, favorable laboratory data are available to indicate that the basic principles of the pyrolysis process are sound. Whether or not a workable process can be designed must be determined experimentally on a scale large enough to permit the modeling of the important parts of a full-scale process. A pilot plant facility could be used to determine how the refuse feed should be prepared (shredding or grinding, classification, etc.), how the refuse can be moved continuously through a retort, what effect the hot refuse and pyrolysis products have on construction materials in the retort, what design features minimize the generation of air pollutants, what equipment is needed for controlling the emission of air pollutants, and what size and type of equipment is required to handle a given feed rate of refuse.

When the above information is available, a critical economic analysis should be performed to determine the potential of those process schemes that then appear technically feasible. This study would eliminate undesirable process schemes while indicating areas in which more research and development are justified.

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# VIII. RESEARCH AND DEVELOPMENT NEEDS

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# VIII. RESEARCH AND DEVELOPMENT NEEDS

## A. INTRODUCTION

The growing awareness and concern regarding environmental pollution underlies a series of research and development programs which are the first steps in identifying, reducing and eliminating air pollutant emissions. The National Air Pollution Control Administration, in its attempt to identify air pollutants, their sources, and their effects, has recognized that the incineration of municipal solid wastes is a major contributor, particularly in urban areas. In New York City, for example, it has been estimated by the Department of Air Resources that 19% of New York's particulate air pollution is caused by municipal incinerators. In Chapter IV, it was shown that the quantity of collected solid waste throughout the United States is rapidly increasing. The projection results reported in Chapter VI show a more rapid increase in active incinerator capacity and air pollution. The research and development programs now in progress must, therefore, be expanded and new programs must be planned to meet the technical and economic challenge of solving incinerator pollution problems.

One such plan is the utilization of refuse to replace a portion of the high sulfur fossil fuels now used for power generation. The refuse analysis presented in Chapter IV shows the effectiveness of this concept in reducing sulfur oxide emissions. If burned in the sophisticated type of equipment common to utility steam generation, including electrostatic air pollution control devices, the resulting particulate and combustible emissions would be negligible. The National Air Pollution Control Administration is presently sponsoring a program to examine all aspects of such schemes. Projections show that the demand for fossil fuel combustion is increasing rapidly, despite increasing electric power generation with nuclear fuels. Moreover, if solid wastes can provide a portion of this combustion energy demand to generate high pressure steam for electric power, a sizable decrease in municipal incineration air pollution and in sulfur oxides emissions might be anticipated.

The program just described, however, will provide only one of the many solutions required to control the air pollution problems of solid waste disposal. For many communities, electric generating plants are not within economic hauling distance. For others, the quantity of refuse available for use in such a combined firing plant is too small to justify the capital investment required. For such communities, where more conventional incineration concepts are needed and appropriate, system technology is needed to enable the design of modern and efficient plants which will not pollute the air. Unfortunately, this technology does not yet exist. In Section B of Appendix H, the evolution of the incinerator is briefly presented. In comparison to the hand-stoked hearth units installed in the early part of this century, many existing plants show great improvement: reflecting the efforts of vendors, engineers, and municipal governments to improve performance. Still, high-efficiency particulate control systems are necessary to obtain acceptable effluent quality; combustible pollutant emissions are unacceptably high, and existing technology is unable to provide reliable solutions. The rapid increases expected in the number and size of incinerators do not permit a perpetuation of the unstructured, empirical development of incinerator design. We cannot continue to build inadequate plants lasting 25-35 years, which tax the financial resources of the municipalities, inhibit additional investment in correction, and spew great amounts of particulates, smoke and carbon monoxide. Fundamental and applied engineering research is necessary to assure that the incinerators forecast to be operating in the year 2000, having a $2 billion investment value, do not fit this valid description of the typical incinerator operating today.

## B. PURPOSE AND SCOPE

In order to upgrade existing incinerator equipment and to provide improved systems with better air pollution characteristics, a series of research and development plans have been developed. The needs served by these plans were identified from the data survey and analysis carried out in the course of this study. In some instances, sections of this study and work by others have been directed towards fulfilling these needs. In other cases, these R&D programs represent areas that have not yet been explored in depth. In all cases, however, the specific research and development programs, discussed in conjunction with their priority rating and costs, represent estimates of the level of effort required to successfully meet the challenge of municipal incineration air pollution control.

Several of the R&D programs are oriented towards obtaining a fundamental understanding of the incineration combustion process and the nature and quantity of municipal refuse. The R&D plans and the ratings accompanying these plans, however, are focused primarily on the air pollution abatement problem and will not be directly concerned with the complex problems associated with the management of solid waste.

Solid waste management practices, municipal incineration, and incinerator air pollution, however, should not be viewed as independent areas for study. For example, Chapter V showed the effect of solid waste composition on incinerator emission and Chapter VII showed the effect of solid waste quantity on the rate of incinerator installation. Also, local collection economics are important in site selection and size. Clearly, optimum solutions to solid waste problems will require an integrated and comprehensive approach; combining the skills of technologists from the combustion, pollution control and engineering sciences with those of economics, marketing, and social sciences. To encourage such interdisciplinary efforts, strong consideration should be given to joint funding of research, multi-agency participation in testing programs and similar partnerships between such agencies as:

- The National Air Pollution Control Administration (NAPCA)
- The Bureau of Solid Waste Management (BSWM)
- The U.S. Bureau of Mines
- The Department of Housing and Urban Development (HUD)
- The Department of Defense (Facilities)
- State Resource Commissions, Air Pollution Agencies and Conservation Boards.
- Municipal Governments, County Agencies, and Regional Solid Waste Management Authorities

Although economic efficiency in research expenditures is an important goal in itself, more than that is gained by collectively seeking solutions to common problems. The overall solid waste management problem is complex. Incinerator location, for example, has social implications which suggest the need for large remote sites, while collection economics press for increased numbers of smaller plants in core-city locations. Air pollution considerations encourage the dismantling of the older high-emission plants, while municipal construction fund limitations force continued operation. Defining such needs and constraints, and identifying acceptable solutions cannot be done unilaterally with the expectation of success.

## C. APPROACH

During this study, numerous individuals and companies directly concerned with all aspects of incineration were contacted. Based both on these interviews and on our review of the present state of the art, an extensive list of research and development needs, focused on reduction of municipal incineration air pollution was compiled. We have listed them here for your convenience.

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The following sections present individual research and development programs for each of seven major categories. The objectives of each program are stated, with brief discussions of the present state of development and the proposed program description. The interdependencies of each R&D plan and other programs are also discussed. Priority ratings, manpower requirements, and costs are also presented for each program. Priorities are listed as being high, medium, or low, reflecting what we believe to be the level of importance in meeting the program objectives.

In Sections K and L, overall five-year programs are developed with expenditure levels of $5 million and $16 million, respectively. For each of these two five-year programs, objectives are discussed, with a table showing the individual R&D plans and their time sequence, comprising the total program. In addition, a figure is presented to illustrate graphically the dollar expenditure over a five-year period.

## D. THE MAGNITUDE AND NATURE OF THE SOLID WASTE PROBLEM AS IT AFFECTS AIR POLLUTION FROM INCINERATION

In Chapter V, it was shown that the nature and quantity of incinerator pollutants are significantly influenced by the characteristics of municipal refuse. Several inherent physical and chemical properties of municipal solid waste directly affect the combustion processes, which in turn influence the combustible pollutant emission characteristics. In addition, certain elements found in refuse result in the emission of noncombustible gaseous pollutants (e.g., $SO_2$, HCl) released in the combustion process but usually independent of the design and operation of the incineration system. Also, certain materials in refuse have soot-forming tendencies, while others may result in the formation of mineral particulate. Therefore, a more quantitative knowledge of these chemical and physical refuse properties and characteristics is necessary to better understand the mechanisms and extent by which these refuse-dependent pollutants will be formed.

In Chapter IV, all available solid waste composition data were analyzed to define a "national annual average" composition. While use of this "average" composition concept was justified to provide input to the projection model presented in Chapter VI and for other purposes, several limitations and simplifications are inherent in the analysis. The limited amount of credible data (32 sets) available for the analysis and the importance of accurate refuse composition information in assessing incineration and incineration air pollution problems, justifies additional effort: seeking both national and localized averages. Of particular importance is the fraction of plastics (especially polyvinyl chloride as it relates to HCl emission).

Perhaps of greater importance would be the collection of data on the chemical, physical and thermodynamic properties of specific refuse components. Data pertaining to ultimate analysis, heat content, and proximate analyses (moisture, volatile matter, fixed carbon and ash) are limited to the values reported by Kaiser (see Chapter IV and Appendix C). Additional data should be developed using standardized techniques: building upon those recommended by the BSWM, the Bureau of Mines, etc.

These programs should not only cover the determination of the inherent physical and chemical properties of refuse, but methods to reduce emissions by alteration of these properties before charging to an incinerator should be considered. One inherent characteristic of refuse is the variability in heat content. This variability could be reduced, to some extent, by the addition of either water or substances with a high heat value, to decrease or increase the refuse heat content as needed, to maintain a relatively constant refuse heating value. The elimination of this variability would improve the completeness of combustion by stabilizing incinerator operation, thus allowing optimum positioning of air control dampers, grate speeds, etc. Reduction in combustible pollutant emissions should be effected by such operating practices.

Research and development programs in this area are also needed, to predict the future distribution of refuse disposal facilities among the available alternatives. The most direct method of alleviating air pollution from incineration is to replace incinerators with other refuse disposal alternatives which are not sources of pollution. Improved prediction of the market share of incineration relative to other disposal alternatives will better quantify the significance of the air pollution problem from incineration in the future.

### 1. R&D Program – *Mobile Laboratory*

*Objective:* Design and construction of a mobile laboratory for the analysis of incinerator solid, liquid, and gaseous streams.

*Discussion:* The requirements for sampling and subsequent analysis of municipal refuse and other incinerator streams indicate the need for the on-site operation of a mobile sampling laboratory. Such a laboratory would eliminate several problems associated with the shipping of samples from the site to a laboratory. For example, nitrogen oxides, hydrocarbons, and sulfur oxides in gas samples may react during this lag time. Parametric tests, which may be based on the results of previous tests, could not be efficiently carried out because of this time lapse. There are also problems associated with the possibility of moisture loss and damage to samples during shipment. A mobile sampling laboratory would, therefore, be a valuable tool in carrying out on-site incinerator testing.

*Program Description:* The program is visualized to be carried out in two phases. Phase I would be concerned with the design of the laboratory, and Phase II would involve the construction of such a facility.

*Phase I* (8 months)

The design of a mobile laboratory should incorporate the flexibility to carry out several types of analyses on solid waste materials as well as liquid and gaseous effluent streams. The design should also reflect the objectives and scope of on-site testing programs. Clearly, the contributions of NAPCA, BSWM, FWPCA, and other government agencies having interest in this mobile laboratory are needed.

*Phase II* (8 months)

Once an appropriate design is developed, the construction of such a facility can commence. In this phase, specifications for bidding would be prepared, with bid evaluations, contractor selection, and procurement.

*Priority: High*

| | | | |
|---|---|---|---|
| *Man/Year Requirement:* | Phase I | – | two professionals, two draftsmen |
| | Phase II | – | two professionals, and construction labor |
| | | – | two professionals, and con- |
| *Cost:* | Phase I | – | $150,000 |
| | Phase II | – | $100,000 + 100,000 construction costs |
| | Total | | $350,000 |

2. R&D Program D-2 – *Refuse Properties*

*Objective:* Estimation of the physical and chemical properties of refuse.

*Discussion:* Since air pollution emissions from incinerator stack gases are so intimately related to the combustion process, a knowledge of the properties of refuse which influence combustion is important. These properties not only influence overall combustion performance, but they may also directly affect the quantities of soot and fine ash entrained in the flue gas, as well as the nature and quantity of other pollutants.

Only a very limited amount of experimental data exist on such refuse properties as:

- heating value,
- % moisture,
- % combustible,
- % volatile matter,
- % ash, and
- ultimate chemical analysis.

Studies are needed to improve and update the existing data bank and to determine the sensitivity of these municipal refuse properties to seasonal and geographical variations. With these data, correlations of emission rate and refuse properties, such as those explored in Chapter V, could be refined to suggest more convincingly and quantitatively the benefits of alternate design and operating practices. Such data would also be of great value to incinerator designers and investigators of refuse and incinerator combustion processes.

Specific elements and compounds present in the refuse, such as selenium, metal salts, sulfur, certain metals (Sn, Pb, Cd, Zn) and halogenated polymers form such pollutants as sulfur oxides, volatile metal oxides, or hydrogen halides in the incinerator environment. The presence and concentration of these pollutants in the effluent may be predicted by identifying specific elements and compounds in refuse materials. However, there are very few data on the concentrations of these trace materials in refuse.

The various components of municipal refuse should be analyzed to determine their chemical make-up, including trace impurities. Modern analytical techniques should be employed. The chemical form in which those elements having pollution potential exist should also be determined. This would help predict the reactions that will take place in the incineration combustion chamber and would suggest the resulting products which will be generated. This task is a complicated one, considering the numerous, varying components of municipal refuse and the complex, varying reaction conditions existing in municipal incinerators. A field study to confirm the appearance and concentration of these pollutants in incinerator emissions is a necessary second step in this evaluation.

*Program Description:* The refuse from a number of municipalities throughout the country should be evaluated. These tests should be designed to show both seasonal and geographical variations in composition. Analyses should also be done on specific refuse components, in order to identify specific elements and compounds which may affect incinerator emissions. Test procedures should be developed, to predict the composite refuse properties listed above. In addition, these properties should be estimated for each major category in municipal refuse (i.e., paper, and plastics). This is necessary, so that as the composition of municipal refuse changes in the future, the properties of each refuse component can be weighted appropriately to develop estimates of future municipal refuse characteristics.

This effort would be dispersed over two years.

*Interdependencies:* The mobile laboratory discussed in Program D-1 would prove to be of value in the implementation of this test program. Therefore, the completion of Program D-1 might be advisable, prior to the initiation of this plan. If, however, the completion time of Program D-1 is delayed, this test program could proceed in conjunction with Program D-1, and the mobile laboratory could be utilized when completed.

*Priority:* High.

*Man/Year Requirements:* ten professionals, ten technicians

*Cost:* $750.000

### 3. R&D Program D-3 – *Refuse Composition Forecasts*

*Objective:* Projections of refuse properties into the future.

*Discussion:* Because of the significant influence of the refuse properties (discussed in Program D-2 Section D) on the nature and quantity of incinerator air pollutants, their future values should also be estimated. The results presented in Chapter IV indicate the predicted trends in such key variables as refuse heating value, percent moisture, percent volatile carbon, and percent ash. Further studies are recommended to expand and update this type of projection analysis.

*Program Description:* The individual growth of the ten basic categories now comprising municipal refuse should be estimated together with any predicted changes in the vital physical and chemical properties of that category. These projections should consider the influence of shifting buying patterns and marketing innovations (i.e., PVC beverage containers) affecting refuse composition. The properties of municipal refuse can then be forecast by utilizing the base year values developed in Section D, Program 2 for each refuse category, and the relative growth rates of the categories. The projection techniques presented in Chapter IV may be useful here.

This is a one-year contract effort with subsequent updating by NAPCA, BSWM, etc.

*Interdependencies:* The key refuse properties to be projected and the present values of these properties which serve as the reference point will be developed in Program 2, Section D. The implementation of Program 3 is, therefore, highly dependent on information generated from 2.

*Priority:* Medium

*Man/Year Requirement:* one professional

*Cost:* $50.000

### 4. R&D Program 4 – *Gaseous Pollutant Emission Forecasts*

*Objective:* Projection of future emission quantities of noncombustible gaseous pollutants from incinerators.

*Discussion:* In order to evaluate the future pollution potential of noncombustible gaseous pollutants from incinerators, the quantities of these substances must be projected into the future. The estimates of these present pollutant quantities as developed in Program 2, Section D, will serve as a base from which to project. Also, the magnitude of these base values will indicate priorities in estimating future trends.

*Program Description:* Projections should be developed for those refuse components containing elements which contribute to the formation of noncombustible gaseous pollutants. Projections of key refuse components should consider the future appearance of substances in refuse other than those presently identified which may contribute to the pollution problem. Consideration should be given to shifting buying patterns and possible legislative actions, as they affect the refuse components being considered.

This is a one-year contract effort with subsequent updating by NAPCA, BSWM, etc.

*Interdependencies:* This R&D program is highly dependent on the results obtained from Program 2, Section D, which identifies and develops emission loads for the present noncombustible gaseous pollutants. These present values will serve as a base from which to project future pollutant quantities. In addition, these projections might be performed in conjunction with the prediction of other pollutants.

*Priority:* Low

*Man/Year Requirement:* one professional

*Cost:* $50,000.

### 5. R&D Program 5 – *Refuse Heat Content Control*

*Objective:* Limiting the variability in refuse heat content by the addition of controlled quantities of water or waste oil.

*Discussion:* Municipal incinerators are generally designed to consume refuse within a range of heating values. However, factors such as rain, or the lack of it, together with day-to-day and seasonal variations in refuse composition, often shift the heating value below or above the design range, adversely affecting burning capacity and increasing air pollution emissions.

After a heavy rain, it is not uncommon for refuse moisture content to rise as high as 50%. As described in Section C of Appendix H, and illustrated in Table C-1 of Appendix C, such high moisture content greatly depresses the temperature levels in the furnace and within the burning bed. A great increase in combustible pollutant emissions occurs under these conditions. A second effect of burning wet refuse is the increase in mineral particulate emissions, which accompanies an increase in underfire air rate (used by the operators to encourage burning in the bed).

The controlled addition of water or auxiliary fuel could be successfully employed to adjust the refuse Btu content to within design limits. The problem in the past, however, has been the high cost of fuel. This program will examine the technical feasibility of utilizing waste crankcase oil in place of fuel oil or natural gas to supply the incremental heat content necessary for wet refuse. Waste crankcase oil is inexpensive and large quantities are readily available in most municipalities. In many cities, use of the waste oil in this manner will provide a service in effecting disposal of a difficult waste material.

*Program Description:* A series of experiments should be designed to examine the technical feasibility of utilizing waste crankcase oil to increase the average heat content of refuse. This can be tested initially in a small unit and verified in a commercial-scale plant. If successful, designs should be made of a spray system which adds either water or waste oil to the refuse, depending on its "wetness," in the pit or at another injection point prior to firing. Clearly, questions of fire safety and air pollution increases associated with the use of waste oil must be explored.

Standard correlations between operating temperatures, percent of excess air, and refuse heat content will allow the operator to adjust his waste oil or water addition as governed by his furnace temperature and percent excess air.

This is a one-year program.

*Interdependencies* None

*Priority:* High

*Man/Year Requirement:* one professional, two technicians

*Cost:* $100,000

### 6. R&D Program D-6 – *Forecast of Disposal Trends*

*Objective:* Prediction of future market shares of refuse disposal alternatives.

*Discussion:* This report, as well as others, has estimated the future market share of incineration in comparison to the combined total of other disposal alternatives. These studies are somewhat subjective in nature and have not developed market predictions for specific refuse disposal techniques other than incineration. Limited credible information is available on predicted use of landfill, rail haul, composting, or other alternative refuse disposal schemes. Such information will be of use in anticipating future incinerator air pollution.

*Program Description:* The markets for each of the existing municipal refuse disposal alternatives should be established, and should be projected into the future, with other potential techniques not presently utilized. These should be done for each alternative and then related to the predicted refuse generation rates, in order to estimate the market share that incineration will experience in the future. This information will help define the magnitude of incinerator air pollution in the future.

This is a one-year program.

*Interdependencies:* This program can proceed relatively independently of the other R&D plans.

*Priority:* High

*Man/Year Requirement:* one professional; 1/2 technician

*Cost:* $70,000.

## E. THE MAGNITUDE AND NATURE OF AIR POLLUTION FROM INCINERATION

The data presented in Chapter V and Appendix J summarize all available public information on incinerator emissions. Information on gaseous pollutants is very limited, as most of the past testing programs have emphasized study of particulate emissions. Available particulate emissions data are limited, however, and are not presented with a comprehensive statement of the operating variables of the incineration system being tested. In some instances, the validity of the values presented are questionable.

Chapter V presents the results of an analysis seeking to identify quantitative relationships between design and operating parameters. Although the correlations and relationships suggested are useful, incomplete or scattered data too often required application of factors based on judgment or produced statements regarding general trends, rather than quantitative correlations. In order to resolve these uncertainties, new data are required.

This lack of available emissions data necessitates the development of new and reliable information, based on accepted and uniform experimental techniques. Initially, a program should be developed to standardize incinerator emission test procedures. These should include procedures for sampling, handling of samples, subsequent analysis, and reporting of information. As seen in Appendix J, data are reported in varying units, which make comparisons extremely difficult.

In addition to the development of uniform incinerator test methodology, a series of coordinated testing programs, including measurement of pertinent system variables, should be carried out on municipal incinerators across the country. These programs will help to quantify the existing pollution load and will relate these emisssion characteristics to key design and operating parameters. The information obtained from these analyses will not only help to suggest improvements in design and operating parameters, but will also help to develop appropriate design criteria for APC systems. Emission characteristics, such as size distribution and combustible content of particulates are necessary data for the design of incinerator combustion chambers and high-efficiency APC systems.

Once the present incinerator air pollution problem is better defined, projections are then desired, to predict future air pollution levels. Chapter VI presents a projection model for future pollution emissions. This model, however, should be expanded and updated as more quantitative and comprehensive emissions data and emission correlations become available.

### 1. R&D Program E-1 – *Emission Test Methods*

*Objective:* Development of standard incinerator emission test methodology.

*Discussion:* Particulate emission tests have been performed on numerous incinerators throughout the United States, usually in conjunction with overall performance studies following completion and startup of new systems. Table J-1 of Appendix J reports over 300 incinerator emission test results. These emissions data are reported in a variety of units, using a number of different sampling and data reduction methods, and under operating conditions which were seldom referenced with the emissions data.

In addition to the variation in procedures utilized to generate data on particulate emissions, very little information is available on gaseous pollutants, such as hydrogen chloride (HCl) and sulfur dioxide ($SO_2$). The development of standardized testing procedures should therefore include procedures for determining the total pollution load:

- gas composition
- total particulate load (including and excluding condensibles)
- particulate composition
- particle size distribution
- composition of condensibles

*Program Description:* Sampling procedures should be developed and tested for particulate and gaseous pollutants. Optimum sampling locations which take into account the nonuniformity of flue gas velocity, temperature and composition should be determined both prior to and following the air pollution control device. This effort includes sampling procedures and locations for measurements within the furnace. Standardized sampling procedures may also require the need for special sampling probes, especially for tests on pollutant concentrations in the furnace.

Standardized analysis techniques should also be developed and tested for reliability, unit cost, and operational simplicity. These include not only the laboratory analysis, but also techniques for handling the samples prior to analysis. A common basis should be chosen on which to report the data.

An important aspect of these standard emissions test procedures is the identification of pertinent operating variables which should be measured coincidently with emission tests. Contributions from other R&D programs discussed below will be useful here. In this manner, test results can be related to operating parameters, so that the influence of various operating variables on test results might be better understood.

In developing this standard emissions test methodology, interviews should be conducted with a variety of governmental and private testing agencies, professional societies, and vendor firms to obtain the benefit of their experiences. Of particular importance are the contributions of the Power Test Code Committees of the American Society of Mechanical Engineers and the Incinerator Institute of America. Their comments and opinions should serve as vital efforts in the development of the standardized test and reporting methodology. Clearly, the comprehensive analytical and test methodology now under development by NAPCA and BSWM represents a strong starting point for this effort.

This is a one-year effort.

*Priority:* High

*Man/Year Requirement:* two professionals: two technicians (in addition to others now working on parallel studies).

*Cost:* $150,000

### 2. R&D Program E-2 — *Incinerator Testing*

*Objective:* Identification of pollutants by analyses of municipal incinerator influent and effluent streams.

*Discussion:* Because of the completeness of the process occurring in an incinerator, the ultimate form in which entering materials leave the incinerator is often difficult to predict. Combustible gaseous and particulate substances which are not fully oxidized may leave in the residue or may be emitted with the flue gas. Fine ash materials may leave with the residue or may be carried off the bed and entrained into the flue gas stream. Refuse components identified in Program D-4, as being potential contributors to gaseous noncombustible pollutant emission may form other volatile or non-volatile compounds, or may not react at all. These elements may leave either through the stack or as part of the residue ash.

To develop further understanding of the incineration process and to better predict the quantity and nature of incineration pollutants, a series of analyses should be performed on all input and output streams. These analyses will be designed toward closing the overall material balance around the incineration facility and toward closing the material balance for key elements in the refuse which have air pollution potential.

The results of such studies and material balances will be of great importance in the analysis and solution of air pollution problems, particularly in the following areas:

- In Chapter V, for example, a relationship was suggested between the fine particle size residue content of refuse (thus excluding the residue of glass and metal) and particulate emissions. Because of the limited amount of refuse and residue analysis data, this hypothesis could not be quantified.

- The fate of sulfur compounds in an incinerator is uncertain. In Chapter V, it has been suggested that most of the sulfur either remains in the residue or is captured by the fly ash. This postulated mechanism to explain low sulfur dioxide ($SO_2$) emission is given strength primarily by residue analyses. Better gas composition (and corresponding refuse composition data) is necessary to prove or disprove this proposed mechanism. Also, reported data on the presence of sulfur trioxide in incinerator effluents cannot be reconciled with refuse composition, $SO_2$ oxidation mechanisms, or consideration of combustion processes occurring in the burning bed. Definitive data which discriminates between the sulfur oxides and other acid gases is necessary.

- The analysis in Chapter V assumes that hydrogen chloride emissions arise quantitatively from the combustion of polyvinyl chloride in refuse. Tests should be run to confirm this assumption, especially in light of the public concern regarding this pollutant.

- The data presented in Chapter V on carbon monoxide (CO) emission suggests that incinerator emission factors are much larger than the previously-reported values. Also, a factor, called the Mixing Effectiveness Factor (MEF), is defined to suggest the effect of different levels of mixing intensity on emission of combustible pollutants. The emission factor for hydrocarbons is also uncertain. Data are needed to establish better CO and hydrocarbon emission factors, and to evaluate the MEF concept and its relationship to engineering design and operating parameters.

It should be noted that testing programs are now in progress under NAPCA and BSWM sponsorship. The experience and data gathered in the course of these efforts will be very useful in this effort. Indeed, the coordination of such test programs, between these and other interested parties, is strongly suggested for optimum efficiency and data comparability.

*Description:* A series of analyses designed to close the overall incineration material balance as well as the material balances for key potential pollutant contributors should be planned for a few selected municipal facilities. Streams of interest include:

a. charged refuse
b. residue ash
c. gases (including particulate) within the furnace, ducts, and stack
d. inlet water
e. outlet water
f. captured particulate in APC devices
g. materials collected in water-treating systems
h. particulate buildup within the incinerator.

Another aspect of this study is determining the particle-size distribution of particulate pollutants. Because of the complexity of this procedure, it is discussed as a separate study in Program E-3.

These analyses should be carried out over several days of operation to smooth out any short-term perturbations in the system. In addition, the sampling and analyses performed on the flue gas stream should be subject to the testing methodology developed in Program E-1. Incinerator sites to be tested should be chosen to represent a cross-section of the incinerator design and operating practices evident in U.S. practice.

Because of the extended period of time required to successfully complete such tests, it would be beneficial to perform the analyses at the test site. A mobile laboratory such as the one discussed in Program D-1 would expedite this study and reduce costs.

This program is spread over two years.

*Interdependencies:* The test programs as discussed above could be more efficiently carried out with the use of a mobile laboratory such as the one discussed in R&D Program 1, Section D. In addition, this study would depend upon inputs from the laboratory program which identifies potential noncombustible gaseous pollutants. The implementation of the test methodology developed in Program E-1, for flue gas sampling and analyses would also be desirable.

*Priority:* High

*Man/Year Requirement:* ten professionals, four technicians

*Cost:* $600,000

### 3. R&D Program E-3 – *Particulate Size Distributions*

*Objective:* To determine the particle-size distribution and composition of solid pollutants.

*Discussion:* The particle-size distribution of solid pollutants is primarily significant because:

- Such a distribution serves as a basis for APC systems design. The distribution below 2 microns is of special significance, as it represents that portion of particulate matter which is most difficult to remove. Electrostatic precipitators and bag filters are inherently capable of removing many of these particles but knowledge of their particle-size distribution and electrical nature of the solids is instrumental to the design of such systems.
- The combustible particulate size distribution would be helpful in determining the combustion conditions necessary for their destruction.
- Correlations of the size distribution of particulate with design and operating parameters will assist in identifying low pollution potential systems designs and operating procedures.

In determining the overall particle-size distribution of pollutants, screening techniques are commonly employed. For particles less than about 50 microns, however, this procedure is not applicable. Identifying the particle-size distribution of particles smaller than 50 microns is extremely difficult. There are difficulties in obtaining representative samples, and it may be necessary to prevent the agglomeration of smaller particles, prior to analysis. The particles themselves are of random geometries, causing problems in defining particle size.

There are a number of techniques presently utilized for identifying particle sizes, but none of them directly measure the particle size of small particles. Instead, these methods depend on various physical or aerodynamic characteristics related to particle size, such as settling velocity, mass effects, optical properties, or electrical properties. Therefore, in addition to data describing the particle size distribution of furnace effluent solids utilizing screening techniques, there is a need for developing procedures which will result in knowledge of particle shape factors, size distributions, and the effects of key design and operating parameters on these quantities. It should be noted that such procedures will have applicability to a wide variety of particulate sources.

*Description:* Techniques will be developed for sampling and handling prior to analysis. In addition to performing a screen analysis on these solid pollutants, new or existing techniques should be evaluated which determine the particle-size distribution of particles below 50 microns. Once an optimum technique is developed, experimental programs should then be designed to examine the effects of such parameters as refuse feed composition, and key operating and design variables on particle-size distribution. These tests and analyses should be performed on various facilities throughout the country in conjunction with Program E-2. Thorough testing of a representative selection of incinerator units will generate enough data to draw meaningful statistical inferences on particle-size distributions from furnaces of commercial facilities during normal operations.

This is a two-year program.

*Interdependencies:* This study should be carried out in conjunction with Program E-2.

*Priority:* Medium

*Man/Year Requirement:* two professionals, four technicians

*Cost:* $200,000

### 4. R&D Program E-4 — *Total Incinerator Pollution Forecasts*

*Objective:* Projection of incineration pollutant emissions into the future.

*Discussion:* In order to estimate the future air pollution from incineration, the existing data and data obtained in the preceding programs should be used to forecast future incineration pollution. Chapter VI presents the results of such a projection. Existing data, which are presently limited and often do not quantitatively account for operating and design parameters of the incineration system, served as a basis for this projection model. Programs E-1 through E-3 are designed to provide the quantitative data from which to expand and update existing projections.

The results of such forecasts are useful to identify the relative importance which should be placed on incinerator air pollution control. Such information allows the early recognition of pollution crises, giving time for corrective action. The forecasting methods may also be useful in analysis of air-shed pollution levels to incorporate more quantitatively the importance of incinerator pollution.

*Description:* Data generated from such programs as described in E-1 through E-3 in addition to existing data and ongoing emission research should serve as a base from which to project future emissions. A model should then be developed to project these values into the future. The model should be comprehensive, including the flexibility to examine the effect of various parameters on the magnitude of future emissions. The model should consider such parameters as the nature and composition of refuse and the design characteristics of present and anticipated incineration systems. A discussion of the projection model presented in Chapter VI incorporates many features which may well be considered in this projection model.

This is a one-year program.

*Interdependencies:* This program is highly dependent upon the results of such studies as Programs E-1 through E-3, which are designed to generate complete and comprehensive incinerator emissions data for existing systems. The results will serve as a base from which to project future emissions characteristics.

*Priority:* High

*Man/Year Requirement:* one professional

*Cost:* $50,000.

## F. THE CAUSES OF INCINERATOR AIR POLLUTION

The overriding objective in the following R&D programs is to develop design and operating criteria which minimize incinerator air pollution emissions and which also meet the requirements of the other four criteria of performance: cost, reliability, residue quality and safety (see Section D, Appendix H). In order to meet this objective, an array of programs must be implemented to answer questions related to the mechanisms of pollutant formation and control:

- What are the mechanisms of flame propagation through the refuse bed?
- What are the possible or existing means to control refuse burning rates?
- What are the appropriate designs of overfire jets or other means to optimize burnout of combustible pollutants?

- What are the appropriate residence times for complete burnout of combustible particulates and gases?

- What are the mechanisms of fine ash carryover from the refuse bed to the flue gas stream and how can their effect be minimized?

- What are the effects of pneumatic feeding and cyclone burning of shredded refuse on pollution emissions?

- What are the mechanisms of $NO_x$ formation in incinerators and how can their effect be minimized?

The incinerator pollutants which appear controllable by changes in equipment or operating practices fall into three categories: mineral particulate, combustible (carbon monoxide, hydrocarbons, polynuclear hydrocarbons and combustible particulate) and nitrogen oxides. Based on current data (see Chapter V), the parameters controlling the formation and destruction of these pollutants cannot be quantitatively related to emission. The following variables, however, have either been strongly related or are suspected to relate to incinerator pollutant emissions in conventional systems (listed in decreasing order of suspected importance).

- Mineral Particulate
    - Undergrate air rate (cfm/sq ft)
    - Refuse fine ash content (excluding metal and glass residue)
    - Gas velocities in furnace chambers and flues
    - Agitation
    - Effects of unit size (natural convection, wall effects, etc.)

- Combustible Pollutants
    - Mixing effectiveness in chambers and flues
    - Excess air level
    - Lower refuse heating value
    - Underfire air rate
    - Volatilized carbon content of refuse (total minus fixed carbon)
    - Residence time of gases in hot zones

- Nitrogen Oxides
  - Furnace heat release rate (Btu/hr)
  - Combustion characteristics of refuse pyrolysis gases.

In order to quantify the relationships between these parameters and emissions using a theoretical approach only would be too costly if, indeed, such a goal could be realized in view of the complexity of the process. However, a level of understanding sufficient to allow several-fold reductions in pollutant emission is a reasonable goal. Such an objective should be approached on three fronts: theory, controlled sub-scale experiments, and full-scale demonstration tests.

Some of the available combustion, heat transfer, and fluid dynamics theory is presented in Chapter V and in Section C of Appendix H. Although by no means suggesting the full scope and authority of applicable modern furnace design technology, the concepts presented there provide the starting points for a more detailed analysis. Such an analysis, however, must be closely associated with engineering research which provides comprehensive data for comparison with theoretical predictions and correlations.

The many difficulties involved in controlling the operating parameters of a conventional incineration facility during normal operation suggest that many of the tests and programs discussed above could not be effectively carried out in a conventional system. Several of these programs should, therefore, be initiated at the laboratory and/or pilot plant scale, where controlled conditions can be maintained prior to final verification at commercial facilities. Experimentation at these levels will help to develop an understanding of the mechanisms for pollutant formation and will identify the various operating and design parameters which most significantly influence pollutant emissions. Based on these analyses, more efficient incinerator designs can be implemented with comprehensive operating procedures to more effectively limit incinerator pollutant emissions.

It should be noted that the efforts presented below offer numerous opportunities for joint sponsorship; particularly between NAPCA and BSWM. Tests on the pilot incinerator, for example, seek solutions to both waste disposal and air pollution problems. Also, these tests provide an ideal opportunity to evaluate test methods for refuse, air pollution, emissions, residue quality, scrubber effluent quality, etc. Data from such tests will be of great interest to such groups as the American Society of Mechanical Engineers Power Test Code committees. Undoubtedly, these professionals will have considerable interest in active participation in test planning and data analysis.

### 1. R&D Program F-1 *Pilot Incinerator Design*

*Objective:* Development of design criteria for an incinerator test system.

*Discussion:* The types and quantities of air pollutants emitted from incinerator stacks are highly dependent on the combustion process within the primary incinerator chamber. Investigations of the various operating and design parameters as they affect combustion and air pollution have, however, been limited to small, batch-fed units. Some investigations, such as the study of the effects of overfire air on combustible pollutants, have been carried out in commercial incinerators but very few quantitative and comprehensive engineering data are available. In order to obtain better control over the combustion process and to substantially reduce air pollution, this gap in understanding should be closed.

The engineering data necessary to increase understanding can be obtained from existing commercial incineration facilities or from a test facility designed to generate such data. Because of the extreme difficulties involved in controlling the various parameters of a commercial facility during normal operation, a test incineration system is needed. The design of such a facility is critical in order to assure that correlations will be obtained that can be extrapolated to the various types and sizes of commercial incinerators. Therefore, the determination of design criteria for such a test facility is necessary before such a unit can be constructed.

*Program Description:* The significant design criteria and scale-up factors of incinerators need to be determined prior to the design and construction of an incineration test facility. The problem is extremely complex because scale-up factors are not always mutually consistent. For example, the grate area (heat release rate) of a cylindrical chamber is proportional to the square of the diameter. The flow characteristics, however, are proportional to the first power of diameter (through the Reynold's number). Buoyancy effects (modified Froude number), volumetric reaction rates, etc., suggest other dimensional dependencies. These scale-up factors may not be consistent, and priorities must be established, from which a meaningful set of design criteria can be developed. The ultimate design shall allow for flexibility to examine the effects of typical design parameters:

- grate area,
- overfire and underfire air rates,
- refuse feeding techniques,
- ignition arch placement;
- overfire jet location, and
- flue gas residence time.

This program will ultimately produce detailed design drawings, from which such a facility can be constructed. Also, the detailed design and/or selection of instrumentation and controls would be included since this facility will be utilized for experimental work, the instrumentation and control systems will be a vital and integral part of the facility. The incinerator system analysis will also be useful in experimental design and data analysis.

This is an 18-month program.

*Interdependencies:* R&D programs oriented toward use of the data of such a test facility, and other programs that utilize conventional commercial units to verify results from the test facility will all follow this effort.

*Priority:* High.

*Man/Year Requirement:* two professionals, two draftsmen

*Cost:* $150,000.

### 2. R&D Program F-2 – *Pilot Facility Construction*

*Objective:* Construction of an incineration test system.

*Discussion:* Based on the design concepts developed in Program F-1, a test incineration facility should be constructed. Such a facility will be generally used to perform tests and measurements under controlled conditions, and to achieve a better understanding of the mechanisms of incinerator air pollutant generation, control, and the incineration process itself.

*Program Description:* The major emphasis of this program would be the construction and startup of the test facility, including all instrumentation controls and peripheral laboratory facilities. Because the optimum size and capacity of such a facility have not as yet been established, costs associated with its construction are presently difficult to estimate. The funding of the incinerator building and process equipment will, therefore, be based on estimates for a 25-ton-per-day test unit with additional costs estimated for the instrumentation controls and laboratory facilities. This program would involve the preparation of the specifications for bidding, and the evaluation of bids.

This is an 18-month program.

*Priority:* High.

*Man/Year Requirement:* three professionals, four draftsmen and technicians.

*Funding:* \$250,000 plus \$1,000,000 capital investment for facility, including the associated laboratory and instruments.

*Total Cost:* \$1,250,000.

### 3. R&D Program F-3 – *Fundamental Refuse Combustion Study*

*Objective:* To gain an understanding of the mechanism of propagation of an ignition front through the refuse bed, and of refuse burning rates.

*Discussion:* In order to determine the conditions under which optimum burnout of refuse and pyrolysis products (potential combustible pollutants) can be achieved within the fuel bed, it is essential to understand the combustion processes occurring within the bed. At the top of the bed, refuse is ignited, and the ignition front propagates through the bed. The temperature of the refuse just ahead of the front increases until ignition occurs. Following ignition, the temperature at that point will remain relatively constant as refuse pyrolysis and carbon burnout commence. As the level of combustible material decreases, the local bed temperature will also decrease. Studies are necessary to determine the propagation rate of the ignition front, the heat and mass transfer, and the chemical kinetics controlling combustion. Data regarding $C/CO/CO_2/O_2/H_2O$ interactions will be of concern in controlling CO formation.

*Program Description:* It is anticipated that this study will first be done on a laboratory scale where operating conditions can be closely controlled, the determination of the effects of such variables as

- radiation to the top of the bed,
- refuse bed height,
- refuse particle size distribution,
- underfire air rates temperature and distribution,
- grate characteristics [stoking method, open area (siftings rate), etc.] and

- refuse composition (moisture, heating value, pyrolysis characteristics, ash content, etc.)

on the flame propagation and refuse burnout rates should be accomplished. Also, the effects of overfire and underfire air rates, as well as the type and degree of stoking, should be evaluated. These laboratory tests will be designed to identify the range of conditions under which the rates of flame propagation and refuse pyrolysis gases and residue burnout can be optimized.

This program is spread over two years.

*Interdependencies:* This program will be followed by Program F-5 which will verify the range of conditions for optimum refuse burnout within the fuel bed on a full-scale test unit.

*Priority:* High

*Man/Year Requirement:* two professionals, two technicians

*Cost:* $150,000

### 4. R&D Program F-4 – *Fundamental Mixing Study*

*Objective:* To develop an understanding of jet-induced overfire turbulence.

*Discussion:* A primary cause of highly combustible pollutant emissions in incinerator furnaces is the poor mixing of flue gases within the furnace and flues. Kinetic studies of reactions in incinerators indicate that sufficient average residence time is provided in contemporary furnaces to burn out combustible particulates and gases. The variations in chamber temperature, however, with the large concentration gradients of oxygen in the overfire volume, are believed to limit these combustion reactions. Adequate mixing imparted to the flue gas stream by appropriate design and location of overfire jets would significantly increase the burnout efficiency of combustible pollutants in the flue gas stream, prior to leaving the primary combustion chamber.

Overfire jets have been used in the stoker-fired coal boilers for over forty years. Significant differences exist between the combustion characteristics of refuse in comparison to coal (Section C of Appendix H). However, coal-burning technology provides a strong empirical and theoretical basis from which to begin the development of a parallel technology for refuse incineration. Of particular interest is the use of steam jets to induce mixing, without the high dilution and flame cooling effect common to air jets in incinerator practice. As described in Chapter V and in Appendix K, such mixing technology promises a substantial reduction of combustible pollutant emissions. This program is the initial step in the development of this technology.

*Program Description:* This program is envisioned to be a laboratory study of jet behavior cross-flow to an upward-moving hot gas stream, analogous to the situation in an incineration combustion chamber. The behavior of turbulent non-isothermal jets in cross-flow is predictable using a number of empirical and semi-empirical relationships. However, one needs an understanding of jet behavior for the complex and dynamic conditions characteristic of incinerator flue gases, where combustion reactions in an "inverted flame" distort jet behavior. Also, steam jets which can induce turbulence without large-scale mass addition and without quenching combustion must be studied. Variables such as nozzle diameter, initial air velocity, jet angle, and jet location relative to the upcoming gases should be evaluated. Also, the independent effects of mixing and combustion air supply on burnout of combustible pollutants should be evaluated. This could be accomplished by comparing air and steam jets having dynamically similar flow characteristics. Relationships should be established between jet parameters to provide optimum burnout of combustible pollutants in the flue gas.

This is a two-year program.

*Interdependencies:* This laboratory study will be followed by Program F-6 which will verify the optimum design and location of nozzles in a prototype test system.

*Priority:* High

*Man/Year Requirement:* two professionals, four technicians (over two years)(incremental)

*Cost:* $200,000

### 5. R&D Program F-5 – *Combustion Study, Pilot Scale*

*Objective:* Utilization of Incinerator Test Facility to optimize bed combustion processes.

*Discussion:* Program F-3, which examined the ignition, pyrolysis, and burnout of refuse within the bed, on a laboratory scale, provides the basis for this program. Operating and design practices suggested in Program F-3 need verification in larger, controlled experiments. The pilot facility (Program F-2) is ideal for this purpose. This step in concept evaluation is important, as it provides a much closer approach to realistic operation while allowing for control, flexibility, and high quality instrumentation.

The quantity and distribution of underfire air, with variations in bed height and stoking techniques, are parameters which should be examined in order to optimize furnace burnout rates and minimize combustible pollutant formation. This optimization should consider the residence time of the refuse bed, the heat release rates along the grate, the quantities of particulate and gaseous pollutants emitted in the flue gas, as well as the residue quality. Based on previous experience with coal-fired furnaces and incinerators, opportunities to reduce the residence time on the grate (thus reducing furnace size and cost) may not exist. The optimization of heat release rates along the refuse bed and decreasing the quantity of pollutant emissions, however, appears to be a more attainable goal.

*Program Description:* Variables such as

- furnace design as it affects radiation to the bed;
- underfire air rates and distribution;
- refuse bed height; and
- the nature and composition of incoming refuse

should be examined to optimize the following dependent parameters:

- heat release rates;
- pollutant emissions;
- residence times on the bed; and
- residue quality.

Experiments should be designed to determine the significance of each of these independent variables on the above dependent parameters. Flexibility should be provided in the test system to control the rate and distribution of underfire air as well as to alter furnace design characteristics. Instrumentation should be available for sampling the pyrolytic products above the grate, to determine the conditions under which minimal combustibles and mineral ash particulates are generated and carried off the refuse bed.

This is a one-year program.

*Interdependencies:* This study is dependent upon the results of the laboratory program discussed in Program F-3 as well as the completion of the incineration test system developed in Programs F-1 and F-2. This program will also be carried out with several other studies to be conducted on the incineration test system. These studies are developed in Programs F-6 to F-13.

*Priority:* High

*Man/Year Requirement:* two professionals; two technicians, and use of pilot incinerator test facility – 1/2 year.

*Cost:* $150,000

### 6. R&D Program F-6 – *Mixing Study, Pilot Scale*

*Objective:* Utilization of the Incinerator Test Facility to optimize the design and positioning of overfire jets.

*Discussion:* The laboratory study performed in Program F-4 evaluates the effects of such variables as nozzle diameter, jet parameters and nozzle angle, on the degree of mixing obtained in the flue gas stream and the consequent reduction in the generation rate of combustible pollutants. Program F-4 also indicates the relative effects of oxygen supply and mixing energy on the burnout of combustible pollutants. A range of conditions are selected in F-4 where optimum reduction in combustible pollutants can be achieved. This study will utilize the incinerator prototype test facility to verify the results of Program F-4 before implementing these results in a commercial unit.

The evaluation of jet performance in a prototype system may yield different results than predicted on the basis of the laboratory-scale tests of Program F-4. Two reasons are apparent: the difference between the characteristics of the incinerator flue gas and the synthesized laboratory gas stream; and the difference in configuration between the prototype chamber and the laboratory chamber configuration. However, the basic behavior and jet flow characteristics observed in the laboratory testing can be utilized to shed light upon the ranges of conditions under which optimum mixing and burnout of combustible pollutants can be achieved in a prototype facility.

*Program Description:* The prototype test unit should have the flexibility to vary such parameters as overfire air jet diameter, jet angles and locations of the jets themselves. In addition, steam jets and air jets should be tested to determine the independent effects of mixing energy and oxygen supply on the burnout efficiency of combustible pollutants. Experiments should be designed and carried out, showing the independent effects of these variables and their interactions on the combustible pollutant content of the flue gases emitted from the furnace. Care should be taken to monitor and control the nature and composition of the refuse being fed to the system, and to control other variables affecting the burnout and heat release rates on the refuse bed.

Sampling and subsequent analysis will be performed on the furnace flue gases to determine the spatial distribution, type, and composition of combustible pollutants, both gaseous and particulate. These results will then be related to the operating parameters discussed above, to determine their significance in the combustion process above the refuse bed.

This is a one-year program.

*Interdependencies:* This study is dependent upon the results of the laboratory program discussed in Program F-4 as well as the completion of the incineration test system developed in Programs F-1 and F-2. The program will also be carried out with several other studies on the incineration test unit.

*Priority:* High

*Man/Year Requirement:* two professionals; two technicians (incremental cost)

*Cost:* $150,000

### 7. R&D Program F-7 – *Particulate Study, Pilot Scale*

*Objective:* To establish the mechanisms by which mineral ash (fine ash) and combustible particulate is carried from the refuse bed.

*Discussion:* Because of the small particle size, high aerodynamic resistance (plates), and the low-density characteristic of the mineral ash resulting from incineration of paper and other refuse components; it has been suggested that this material may be readily suspended in the gases rising through the refuse bed and carried out of the furnace. Several counteracting phenomena occur within the primary chamber which affect entrainment. For example, the presence of certain fluxing materials in the refuse might cause agglomeration of ash, preventing this ash from being carried from the bed. The quantity of underfire air and the design of the grates through which this underfire air passes may significantly influence the degree of ash-particle entrainment. Therefore, a study is necessary to establish the mechanisms of ash entrainment in the flue gas stream.

*Program Description:* Experiments should be designed to evaluate the independent effects of such variables as

- refuse composition;
- moisture;
- refuse shredding;
- temperature;
- underfire air;
- overfire air; and
- grate design (especially in regard to air distribution).

It is suggested that the test incinerator facility, rather than a commercial facility, be utilized initially, so that adequate control over the process variables can be maintained. Sampling and analytical techniques for determining the quantities of mineral particulate in the flue gas emitted from the furnace should be established and utilized during the test program.

This is a one-year program.

*Interdependencies:* This study will be performed in conjunction with several other programs, utilizing the prototype unit discussed in Programs F-1 and F-2 above.

*Priority:* High

*Man/Year Requirement:* one professional, one technician (incremental cost)

*Cost:* $75,000

### 8. R&D Program F-8 – *Suspension Burning Studies, Pilot Scale*

*Objective:* To determine the effects of suspension burning (pneumatic feeding of shredded refuse) on pollutant emissions.

*Discussion:* Programs F-3 and F-5 examine the mechanism of refuse burnout and flame propagation within the refuse bed. In those programs, the effects of shredding on these two parameters are evaluated. This study would be concerned with the effects of pneumatic distribution of shredded refuse on the emission rate of particulate and gaseous pollutants.

Two characteristics of suspension feeding have opposing effects in pollutant formation. The relatively small size of the shredded refuse particles (large surface-to-volume ratios), suspended in the turbulent, hot combustion gases, should significantly enhance the burnout of combustible particulate. On the other hand, the small size of these particles would increase the particulate loading. Although the resulting particulate load will be larger than for conventional plants, the particle-size distribution may be displaced toward larger particles that are easier to collect. The size distribution of this particulate and its emission rate are necessary data for the design and selection of APC systems for incinerators based on the suspension-burning concept. These studies may also suggest firing techniques and shredding methods to minimize emissions.

*Program Description:* It is envisioned that this program would be carried out with the prototype test facility discussed in Programs F-1 and F-2. The experiments would be designed to evaluate the effect of suspension feedings on the pollutant emissions, independent of pollutant contributions originating from the refuse bed. Therefore, such variables as quantities of underfire and overfire air should be controlled so that their effects on pollutant formation could be distinguished from those resulting from the suspension feeding of shredded refuse.

This is a one-year program.

*Priority:* High

*Man/Year Requirement:* two professionals, three technicians

*Cost:* $225,000 (including equipment)

### 9. R&D Program F-9 – *$NO_x$ Studies, Pilot Scale*

*Objective:* To obtain an understanding of $NO_x$ formation in incineration systems.

*Discussion:* The oxides of nitrogen have been of increasing concern, because of their role in atmospheric photochemical reactions leading to the formation of smog. The primary sources are automobiles and stationary facilities, such as large power plants. $NO_x$ emissions from incinerators are small, compared to the emissions from these other sources. Unlike the formation of sulfur dioxide, which is dependent upon the sulfur composition on the fuel, the formation of nitrogen oxides appears independent of refuse composition, but is related to combustion conditions such as flue gas residence time, temperature, flame size, and quantities of excess oxygen.

$NO_x$ formation is favored by high excess air levels, high flame temperatures, and steep temperature gradients. Lowering the excess air may retard $NO_x$ formation, as a result of reduced oxygen concentrations. However, increases in flame temperature at low excess air increase the rate of $NO_x$ formation and the equilibrium concentration.

Although typical incinerator flame temperatures of 1800-2000°F do not suggest optimal conditions for $NO_x$ formation, only limited experimental data are available on $NO_x$ emissions from incinerators. Certainly too few data are available to suggest effects of design on the rate of formation. The available data (Chapter V and Table J-2, Appendix J) were only sufficient to establish an effect of unit heat release rate (Btu/hr) on $NO_x$ emission. The combustion conditions or the regions in the incinerator where $NO_x$ is formed are also unknown. A better understanding of $NO_x$ formation in incinerators is therefore necessary so that appropriate design and operating parameters might be adjusted to retard its formation.

*Program Description:* This study involves probing of the incinerator chamber to determine a profile of $NO_x$ concentrations. At these points such variables as temperatures, excess air, and temperature gradients (which indicate degree of heat transfer) would be measured. These data will assist in identifying the design and operating parameters affecting $NO_x$ formation.

This set of experiments could be carried out in the test incinerator facility described in Program F-2. This facility would be desirable because of the extreme difficulty in controlling the various parameters during normal operation on a commercial unit.

This is a one-year program.

*Priority:* Low

*Man/Year Requirement:* two professionals, two technicians (incremental)

*Cost:* $75,000

### 10. R&D Program F-10 – *Studies of Combustible Particulate*

*Objective:* To study and understand the rates of formation and burnout of combustible particulates.

*Discussion:* The objective of Program F-10 is to determine the rates of formation and burnout of combustible particulates from pyrolysis of refuse components. Such data will be helpful in establishing the incinerator design and operating conditions to minimize combustible particulate emissions. Little is known of the mechanisms by which refuse components pyrolyze to form combustible particulate matter. The data gathered (see section VII-E) in studies of the pyrolytic process may be of some use, however. Also data on soot formation in hydrocarbon flames may be pertinent. Chapter V suggests that combustible particulate emission rates are associated with the volatile carbon content of refuse (total minus fixed carbon). This relationship and others coupling refuse composition, heat-transfer rates, chemical environment (oxygen concentration), etc., to particulate formation are needed to gain understanding of methods for reducing such emissions.

At present there are theoretical techniques for estimating the burnout rates of pure carbon as a function of particle size. However, laboratory data are necessary to verify this theory and to extend the analysis to systems of particles characteristic of those generated in an incinerator flame. This study is restricted to combustible particles because much information is presently available on the combustion kinetics of combustible gaseous pollutants where the rate-controlling step has been identified as the oxidation of the carbon monoxide formed as a combustion intermediate.

*Program Description:* If not presently available, laboratory techniques would be developed to study the rates of formation and burnout of particles under conditions which model those of an incinerator furnace chamber. Burnout rates would be determined as a function of both particle size and composition of the refuse materials. Samples of particulate from the pilot incinerator tests should be made available for comparison with those generated under laboratory conditions.

Because the environment of the furnace chamber is extremely complex to model, the laboratory experiments will at best provide an understanding of these processes under very idealized conditions. The results of these laboratory tests will, however, help to confirm whether the degree of the burnout in conventional systems is presently limited by residence time or, in fact, whether burnout is limited by other parameters such as mixing, pore diffusion (in particles composed of mineral ash "coated" with carbon deposits), temperature uniformity, and oxygen supply in the combustion chamber.

This is a one-year program.

*Interdependencies:* This program will be implemented concurrently or after the completion of Programs E-2 and E-3 which will produce well-characterized particulate samples.

*Priority:* High

*Man/Year Requirement:* two professionals, two technicians

*Cost:* $150,000

## 11. R&D Program F-11 – *Full-Scale, Bed-Combustion Study*

*Objective:* Examination of the burning characteristics of the combustion process in the refuse bed in a commercial scale facility.

*Discussion:* Programs F-3 and F-5 are directed towards developing a set of conditions under which optimum burning of the refuse bed can take place. As indicated in these programs, such parameters as the quantity and distribution of underfire air, refuse bed height, and stoking techniques were examined to optimize the grate residence time, heat-release rates, residue quality, and the quantities of combustible and inert particulate matter carried off the refuse bed. This program will be designed to verify the results of these analyses on a commercial-scale incineration system.

*Program Description:* The set of optimum conditions developed in the above-mentioned programs are to be verified in this study. Attention should be given to the selection of the facilities where this verification program will take place. Not only will the program be implemented during normal operation, but additional instrumentation and control, as well as modifications to the design of the grate and feeding systems, might be anticipated. The number of incinerator designs to be covered will depend upon the adequacy of correlations to extrapolate and interpolate to different conditions. The planning and management of such a program will be of key concern to minimize costs and to assure that high quality data are produced.

This is a two-year program.

*Interdependencies:* As mentioned above, this verification program will depend upon the successful implementation of R&D Programs F-3 and F-5. Also, the mobile laboratory (Program D-2) will be useful here.

*Priority:* High

*Man/Year Requirement:* four incinerator tests, four professionals, six technicians

*Cost:* $450,000 (including some equipment modifications)

## 12. R&D Program F-12 – *Full-Scale, Overfire Combustion Study*

*Objective:* Verification of optimum design of overfire jets in a commercial scale facility.

*Discussion:* Programs F-4 and F-6 are directed towards developing the optimum design and evaluation of overfire jets at a laboratory and pilot-scale. Such parameters as jet diameter, angle, location, and momentum flux will have been considered and optimized in these previous two programs. In addition, the independent effects of mixing energy and oxygen supply on combustible pollutants in the flue gas should also have been examined. The results of this effort will validate the effects of changes in jet parameters and yield design and operating methods to reduce combustible pollutant emissions in existing and new incinerators.

*Program Description:* The evaluation of overfire air jet effectiveness should be carried out in at least four different commercial incineration facilities. Much care should be taken in selecting the incineration sites because the nature of this verification study may involve significant changes in the design of the overfire air system presently installed. In addition, the experimental work will be carried out in conjunction with the normal operation of the incinerator; therefore, the close coordination of the modification and testing programs with the municipal sanitation department will be necessary.

This is a two-year program.

*Interdependencies:* As mentioned above, the program is highly dependent upon Programs F-4 and F-6. Also, the mobile laboratory developed in Program D-2 will be useful.

*Priority:* High

*Man/Year Requirement:* (incremental) four professionals

*Cost:* $450,000 (including some equipment)

### 13. R&D Program F-13 – *Full-Scale Particulate Study*

*Objective:* To validate methods to reduce ash carryover from the refuse bed in a commercial scale facility.

*Discussion:* In Program F-7 the mechanisms of fly ash carryover from the refuse bed were examined. Such variables as refuse composition, moisture, refuse shredding, temperature, underfire air, overfire air, and grate design were examined and optimum conditions were developed to minimize particulate carryover consistent with meeting other incineration objectives. The results of this study, however, need confirmation and verification in a commercial facility. The results of this study will yield design and operating concepts useful in existing and new incinerators to minimize particulate emissions.

*Program Description:* A series of tests will be performed with a commercial facility to verify the results of Program F-7. This experimentation will be carried out in conjunction with normal operation although some equipment changes may be required. The effects of underfire air rate, furnace temperature, and refuse composition and pretreatment will be verified in light of the previous laboratory and pilot scale work.

This is a two-year effort.

*Interdependencies:* This program is dependent upon the successful implementation of Program F-7 and should be carried out in conjunction with Program F-12.

*Priority:* High

*Man/Year Requirement:* (incremental) 1-1/2 professionals, two technicians

*Cost:* $250,000 (including some equipment)

### 14. R&D Program F-14 – *Full-Scale $NO_x$ Study*

*Objective:* Verification of the mechanisms of $NO_x$ formation.

*Discussion:* Program F-9 examines the mechanisms of $NO_x$ formation in a pilot scale incineration facility. The results of this program, however, must be verified in a commercial system. Although it is likely that means may be found to reduce $NO_x$ emission, it is unlikely that other considerations (such as plant capacity and temperature limits of materials) will conflict with their implementation.

*Program Description:* It is anticipated that, as in Program F-9, this study will involve probing the incinerator chamber to determine a profile of $NO_x$ concentrations. This profile may identify the specific locations where $NO_x$ is formed. At these points, such variables as temperature, excess air and temperature gradients, will also be obtained to verify the mechanisms of $NO_x$ formation postulated in Program F-9. This effort should be conducted concurrently with Program F-12.

This is a two-year effort.

*Priority:* Low

*Man/Year Requirement:* (incremental) one professional, one technician

*Cost:* $100,000

## G. ADVANCED CONCEPTS – FLUIDIZED BED INCINERATION

The application of fluid bed technology to incineration offers the inherent advantages of excellent heat transfer and mixing characteristics in the combustion zone. Consequently, soot formation may be significantly lowered and complete burnout of combustible gaseous pollutants should result. High fluidizing velocities will result in the entrainment of greatly increased quantities of fine ash materials relative to conventional systems. However, these particles may fall in a particle-size range yielding efficient collection with existing APC devices. In the discussion of the fluid bed concept (see Chapter VII, Section E), it was suggested that particulate loadings comparable to those of fluid bed sewage sludge incinerators might be experienced (with corrections made for relative ash and combustible content). If this is found in practice, very high efficiency APC systems will be required to obtain acceptable stack emissions.

Fluid bed incineration technology promises increased particulate emissions but decreased combustible pollutant emissions. Burnout of combustible solids and gases should be readily effected, at excess air levels which reduce the size and cost of the APC system. Because of the excellent temperature control possible with such systems, $NO_x$ formation can also be minimized by operation at low temperatures and low excess air levels. A third possible advantage regarding air pollution effects would appear if alkaline additives (such as limestone) were found effective in reducing $HCl$ and $SO_2$ emissions. Perhaps, the refuse ash itself is sufficiently alkaline to effect such an absorption.

Fluid bed technology is utilized throughout the chemical process industry, so it is at an advanced stage of development. Because much engineering design and operation knowledge are available, the required research and development efforts necessary to determine the potential for fluidized bed incineration of refuse can be selective. The following programs are designed to provide the necessary information now lacking for successful application of fluid bed technology to municipal incineration.

Fluid bed refuse incineration technology may also be obtained from current research efforts, sponsored by BSWM, where a fluid bed system is used to produce a combustible fuel gas for a gas turbine. This incinerator concept, known as the CPU-400, has been under study for about two years. Component development has emphasized gas-cleaning systems and has resulted in successful operation of a high temperature electrostatic precipitator which removes particulate from the gases leaving the fluid bed. Still, feed system development and heavy ash removal systems require additional research, and system economics are still acceptable. The research programs below would support the CPU-400 and other fluid bed incineration concepts.

### 1. R&D Program G-1 – *The Construction of Pilot Fluid Bed*

*Objective:* Design and construction of a pilot scale fluidized bed unit.

*Discussion:* Before experimental work concerned with the utilization of fluidized bed techniques to incinerate refuse can proceed, a pilot unit should be designed and constructed. The diameter of this unit should be at least two feet. This size is judged to be large enough to overcome the difficulties of small size equipment and is adequate in providing realistic indications of the probable operational problems.

*Program Description:* The first phase of this program would involve the design of a pilot unit. Inputs should be obtained from personnel knowledgeable in the operation and technology of fluidized beds in the chemical process industry. The design of the system should include flexibility in testing different feeding systems for a range of feed particle sizes.

The second phase would be the construction of such a facility. Included in the costs of this phase is the preparation and evaluation of bids, materials, and construction costs.

This is an 18-month effort.

*Priority:* Medium

*Man/Year Requirement:*

| | Professional | | Technician/Draftsman |
|---|---|---|---|
| Phase I | 1-1/2 | | 2 (6 months) |
| Phase II | 2 | + | construction (1 year) |

*Cost:* \$225,000 + \$325,000 (estimated equipment cost) = \$550,000

### 2. R&D Program G-2 – *Fluid Bed Feeding Concepts*

*Objective:* To develop appropriate techniques for the preparation and feeding of refuse to a fluidized bed incinerator.

*Discussion:* Appropriate methods of preparation of refuse feed for the fluid bed incinerator, and systems for handling and disposing of the noncombustible residue must be developed. Methods of removing refuse components such as glass and metals from the refuse (prior to incinerator) or from the incinerator must be demonstrated. Possible approaches include:

- Grinding the refuse to a size range that will feed readily and will simplify removal of residue from the incinerator, or

- Removal of heavy, noncombustible solids prior to incineration by such techniques as coarse grinding, followed by water pulping.

Feeding devices will have to be developed, which will insure adequate distribution of the solids, especially for large diameter systems operating with relatively shallow bed depths. This is necessary so that the major portion of the combustion heat is released within the bed and not in the disengaging space above. The problems of feeding dry refuse are most difficult to solve. Positive feeding systems used in the past with refuse are prone to plugging and bridging. Because of the relatively short mean residence time in fluid beds, the refuse feed should approach a steady flow. In systems using a sand bed, however, the high thermal inertia of the bed reduces the importance of constant feed rate.

To date, very little success has been realized in developing satisfactory refuse feeding devices. In order to test alternative feeding systems, it is recommended that the pilot system discussed in Program 1 of this section be utilized.

*Program Description:* A series of experiments should be designed to test various refuse preparation and feeding systems. A pilot plant facility, such as the one discussed in Program G-1, should be utilized. Funding will not only cover the testing of existing systems, but will also cover the development of new methods which show promise. The procurement of refuse preparation, feed equipment, and installation at the rest site will also be funded by this program. Emphasis should be placed on equipment reliability and low maintenance when operating with a wide range of waste materials.

This is a three-year program.

*Interdependencies:* A pilot unit, such as the one to be developed in Program G-1, should be utilized for this program. The availability of such a test system, therefore, is a prerequisite for this study. In addition, there will be other programs dependent on the use of this pilot unit. Therefore, close test scheduling for each of these programs will be required.

*Priority:* Medium

*Man/Year Requirement:* six professionals, six technicians

| | | |
|---|---|---|
| *Costs:* | Development of system – 2 prof. and 3 tech. | $225,000 |
| | Testing – 2 prof. and 3 tech. | 225,000 |
| | Refuse feed preparation equipment – equipment | 100,000 |
| | | $550,000 |

### 3. R&D Program G-3 – *Fluid Bed Additive Study*

*Objective:* To determine the effectiveness of additives injected into the fluidized bed to remove gaseous noncombustible pollutants.

*Discussion:* An integral part of the fluidized bed pilot test program should be the determination of the effectiveness of specific additions for removal of gaseous noncombustible pollutants generated within the fluid bed, such as hydrogen chloride and sulfur dioxide. Such additives as limestone or dolomite could be added separately to the bed, or with the refuse feed. The high degree of mixing, characteristic of fluid beds, would facilitate the successful application of such additives. Experience in use of fluid bed combustors with limestone addition (for $SO_2$ control) is available from current NAPCA-sponsored research. This concept (addition of alkaline materials for acid gas control) may be of increasing importance in light of the growing importance of HCl emission rates (see Chapter V and VI for emission factors and U.S. incinerator HCl emissions, respectively).

*Program Description:* This program would involve the identification and testing of various additives which may react with the gaseous noncombustible pollutants generated in the fluidized bed. Sampling of the off-gases prior to and following additive injection should be performed to verify the effects of the chemicals utilized. The increase in flue gas volume and formation of additional gaseous or particulate pollutants should also be considered.

This is a one-year effort.

*Interdependencies:* This program is also envisioned to be carried out in the pilot fluidized bed unit. Its implementation is, therefore, dependent upon the availability of such a test facility.

*Priority:* Medium.

*Man/Year Requirement:* 1½ professionals; one technician.

*Cost:* $100,000.

### 4. R&D Program G-4 *Fluid Bed Combustion Study*

*Objective:* To determine combustion times for refuse materials in suspension.

*Discussion:* Information on the residence time required to sufficiently burn out the refuse feed materials is necessary to properly design a fluid bed system. Combustion times of suspended refuse materials are dependent upon such variables as initial particle size, composition, and moisture; the effects of abrasive actions of other particles; fluidizing velocities; and bed temperature. A pilot fluidized bed unit, such as the one described in Program G-1 should be utilized to determine the required residence time as a function of the equipment and refuse parameters.

*Program Description:* Experiments should be designed to determine the effects of the above mentioned variables on the combustion time of refuse particles in suspension. It is envisioned that this experimentation would be performed on the pilot scale fluid bed unit.

This is a one-year effort.

*Interdependencies:* This program is dependent upon the availability of a pilot fluidized bed incineration facility such as the one described in Program G-1.

*Priority:* Medium

*Man/Year Requirement:* one professional, two technicians

*Cost:* $100,000

### 5. R&D Program G-5 *Fluid Bed Economics*

*Objective:* To evaluate the economics of the fluidized bed incineration concept.

*Discussion:* Successful completion of Programs G-1 through G-4 should be followed by a careful appraisal of the relative economic merits of fluidized bed incineration of refuse. If this economic analysis shows that fluidized bed incineration is a competitive concept, a prototype demonstration facility should then be designed.

Alternatively, this program could be carried out at once. The economic data and analysis presented in Chapter VII, Section E, suggests that fluid bed incineration of refuse is economically unattractive in comparison to alternate means. This program would serve to confirm or contradict these conclusions and would identify those items of cost which require reduction to assure the economic viability of the fluid bed concept. Such information would be helpful in guiding and evaluating further research effort.

*Program Description:* This program involves estimates of the capital investment and operating cost for fluidized bed incineration. The investment costs are dependent upon the design of such components as the refuse preparation and feeding systems, as well as the primary fluidized bed furnace and associated instrumentation, controls, and process equipment. The operating costs will be based on experience with the pilot unit and with fluid bed experience in the chemical process industry.

This is a one-year program.

*Interdependencies:* In order to minimize the number of assumptions, input is desirable from Programs G-1 through G-4, which will provide definitive data input to the economic analysis. If the economic analysis shows that fluidized bed incineration is a competitive concept, the way is then clear to begin detailed design work on a full-scale prototype fluidized bed incineration system.

*Priority:* High

*Man/Year Requirement:* one professional

*Cost:* $50,000

### 6. R&D Program G-6 – *Prototype Fluid Bed Design*

*Objective:* To design a prototype fluidized bed incineration demonstration unit.

*Discussion:* The program discussions above, and the discussion in Chapter VII, Section E, have suggested a number of technical and economic problems of fluid bed incinerators. Concurrently, a number of advantages accrue to the fluid bed concept regarding air pollution reduction. If the previous research was able to minimize the problems and verify the advantages, a prototype facility should be constructed for large-scale testing. In this effort, contributions can be anticipated from the previous programs and from the chemical process industries, where the fluidized bed has been utilized successfully for several years.

*Program Description:* The design of a commercial scale fluidized bed demonstration facility will result in a series of drawings and blueprints, from which such a system can be constructed. The design will include the refuse preparation, feeding system, primary chamber and associated process equipment. Also included will be the design or selection of appropriate instrumentation and controls to properly monitor such a system, as well as an effective air pollution control device. The design will also include residue handling facilities and a building enclosure; including offices, locker rooms and other related facilities.

This is a one-year effort.

*Interdependencies:* As discussed above, the design of such a prototype demonstration unit is highly dependent upon the successful completion of Programs G-1 through G-5.

*Priority:* Uncertain

*Man/Year Requirement:* two professionals, six draftsmen

*Cost:* $250,000

### 7. R&D Program G-7 – *The Construction of a Prototype Fluid Bed*

*Objective:* To construct a prototype fluidized bed incineration demonstration facility.

*Discussion:* It may be most appropriate to construct the prototype fluid bed unit near to the pilot incinerator described in Program F-2. This way, duplication of instrumentation and laboratory equipment and the operating staff may be avoided.

*Program Description:* Included in this program would be the preparation and evaluation of bids, and the purchase and installation of equipment. It is envisioned at this time that a demonstration fluidized bed incinerator might have an internal diameter of five or six feet and would be designed for low-pressure operation. It would be hoped that sufficient design and operational information could be obtained from this demonstration unit to commercialize the fluidized bed incineration concept.

This is a one-year effort.

*Interdependencies:* The construction of such a facility is directly dependent upon the successful completion of the design phase.

*Priority:* Uncertain

*Man/Year Requirement:* two professionals, five technicians

*Cost:* $2,000,000 ($1,500,000 if adjoining the pilot incinerator facility.

### 8. R&D Program G-8 – *Prototype Fluid Bed Study*

*Objective:* To carry out demonstration tests on the prototype fluidized bed incineration facility.

*Discussion:* In Programs G-2 through G-4, specific technical advantages and problems were studied. These advantages and the proposed solutions to the problems require demonstration. In contrast to the grate burning systems, fewer variables must be studied for fluid beds; tests are required to demonstrate mechanical and economic acceptability rather than to develop complex design principles. As an example of this difference in test complexity, consider that a fluid bed is almost perfectly homogeneous in composition. Thus, in contrast to grate systems, gas and solid stream sampling is greatly simplified. Also, the rapid response of the bed to changes in operating variables permits rapid exploration of the effect of variable changes.

*Program Description:* Included in this program would be the evaluation of refuse feed and residue removal systems, residue quality, utilities consumption, air pollution characteristics, and (assuming the success of Program G-3) the effectiveness of additives in minimizing acid gas emissions. This program would be carried out on the prototype fluid bed incinerator constructed in Program G-7 above.

This is an 18-month effort.

*Interdependencies:* These tests require the use of the prototype fluid bed.

*Priority:* Uncertain

*Man/Year Requirement:* six professionals, eight technicians

*Cost:* $550,000 ($350,000 if the facility adjoins the pilot incinerator facility)

## H. ADVANCED CONCEPTS – PYROLYSIS

The application of pyrolysis to refuse incineration offers an inherent advantage over conventional incineration processes. As discussed in section VII-E, pyrolysis systems convert refuse from a heterogeneous nonstorable material to three storable products with relatively constant fuel properties which can be burned in conventional furnaces. The flue gas from a pyrolysis unit can be treated with an APC device (severalfold smaller than for comparable grate-burning incinerators) to produce particulate-free gas having a heating value in the range of 200 to 400 Btu/cu ft. The residue char is a homogeneous solid that can be used as a fuel or as a low-grade adsorbent char for applications such as sewage effluent treatment. Metal and glass residue can be readily removed from the char to upgrade the fuel value. A liquid product stream consisting of a mixture of water and organics, such as alcohols, aldehydes, and the like, can be separated into an aqueous and a non-aqueous phase. The non-aqueous phase can be utilized as an internal fuel for supplying heat to the pyrolysis chamber or could be pumped to outside fuel users.

Thus, the pyrolysis process could be a revenue source from the sale of low sulfur fuel products. Combustion of the pyrolysis products should be possible with a minimum of combustible pollutant formation as a consequence of the excellent combustion control possible for homogeneous fuels. Although the relatively low fuel value of the products would not permit their transportation over long distances, perhaps they could be piped directly to a nearby electrical utility or large industrial fuel user. Such customers could burn the pyrolysis products in combination with their existing fuels, probably with conventional burners. Because of the homogeneous and predictable fuel properties of the pyrolysis products, the utilities would expose their boilers to less risk when burning these materials than for raw refuse (the combined firing concept).

Existing laboratory data indicate that refuse pyrolysis can be accomplished readily. Industrial data on coal volatilization suggest that scale-up is possible. The yield of products from different refuse compositions, pyrolyzed at different temperatures, and at different heating rates has received some study. Also, the composition of the gases over a range of conditions is known. However, there are problems and questions related to the pyrolysis incineration concept which need resolution before serious consideration can be given to a prototype or commercial size unit.

### 1. R&D Program H-1 – *Basic Studies of Pyrolysis*

*Objective:* To determine the controlling parameters and products of the pyrolysis of refuse components.

*Discussion:* There are various fundamental questions concerning the nature and characteristics of pyrolysis which can best be answered in the laboratory. These studies should be used to support and guide the design of large-scale experiments. Basic research to determine the controlling parameters of the pyrolytic reaction is needed to predict the residence times required in a pyrolyzer. The effects of such parameters as temperature, gas environment (air, stream, flue gas, etc.), reactor vessel size, and heating rate on the pyrolysis rate and products should be investigated. This effort will complement past work done in this area. Emphasis should be placed on seeking methods to control product composition.

*Program Description:* Experiments to determine the independent effects of pertinent variables on the pyrolytic reactions should be designed. These experiments should be performed on a laboratory scale and should generate the necessary design and operational data needed for construction of a pilot plant facility. Included in this program will be a detailed review of all pertinent existing literature on pyrolysis with consultation with investigators having previous experience with pyrolysis systems. The coal and lignite volatilization literature and gas producer experience should be valuable resources.

This is a two-year effort.

*Interdependencies:* This program should be concurrent with operation of a pilot-scale pyrolysis facility. The information generated in this program will also be very useful in the design, testing, and data interpretation for the pilot scale unit.

*Priority:* High

*Man/Year Requirement:* two professionals, two technicians

*Cost:* $150,000

### 2. R&D Program H-2 – *Design of Pilot Pyrolytic System*

*Objective:* To design a pilot-scale pyrolytic incineration system.

*Discussion:* Existing data on the pyrolysis of refuse and other carbonaceous materials suggest the viability of pyrolysis as a practical refuse conversion process. Testing is required, however, on a scale that is large enough to permit the modeling of important refuse and equipment parameters. A pilot-scale facility could be used, for example, to determine how refuse feed should be prepared (shredding, grinding, classification, etc.), how the refuse could be moved continually through a retort, and what effect the hot refuse and pyrolysis products would have on construction materials. In addition, system energy balances, APC system requirements, and other aspects of design and operation require study.

Identification of the energy requirements for the pyrolyzer will determine what percentage of the energy input to the pyrolyzer retort must be supplied by the pyrolysis products, thus suggesting the importance of by-product "fuel" sales. The effects of air and steam injection on the pyrolyzer and on the quality and quantity of volatile products should also be examined with this pilot facility.

*Program Description:* Based on existing information and the results of Program H-1, a design for a pyrolytic incineration pilot facility should be made. The design should be carried through to the generation of detailed blueprints and drawings and should incorporate the flexibility of examining the variables discussed above.

This is a one-year program.

*Interdependencies:* The design of the pilot-plant facility should utilize the results of Program H-1 and existing data published in the pyrolytic field.

*Priority:* High

*Man/Year Requirement:* one-and-a-half professionals, two draftsmen

*Cost:* $125,000

### 3. R&D Program H-3 – *Construction of Pyrolytic Pilot Unit*

*Objective:* To construct a pyrolytic incineration pilot-scale facility.

*Discussion:* See program H-2 above.

*Program Description:* Based on the design, drawings, and blueprints generated in program H-2, a pilot-scale system will be constructed. This program will not only include the construction of such a facility, but also the preparation and evaluation of bids and the start-up of this pilot-scale unit.

This is a one-year program.

*Interdependencies:* This program is dependent upon the completion of the design of the pyrolytic pilot-scale unit and the generation of appropriate drawings and blueprints. Economy in equipment and personnel can be obtained by construction near the pilot incinerator facilities described in programs F-2 and G-7.

*Priority:* High

*Man/Year Requirement:* two professionals, two technicians

*Cost:* $150,000 + $325,000 equipment cost, or $475,000 ($350,000 if adjoining other test facilities discussed above).

### 4. R&D Program H-4 – *Preparation of Pyrolytic Feed (Pilot Scale)*

*Objective:* To examine techniques for preparation and feeding of refuse for pyrolysis systems.

*Discussion:* Theoretical calculations which indicate that the rate of pyrolysis is limited by heat transfer through the refuse feed materials have been made. The smaller the refuse particles, the faster the rate of heat transfer within the refuse; and, therefore, the faster the pyrolytic reactions can be completed and the smaller the unit for a given capacity. Since pyrolysis systems transform solid waste rather than destroy it, minimum cost may be a prerequisite to its utilization. The size of the refuse feed to the pyrolysis reactor is, therefore, a critical parameter.

At present, there are two techniques generally considered for preparing the refuse feed: shredding and grinding. It is envisioned that these techniques can be examined with a pilot scale pyrolysis system such as the one discussed in H-2. If possible, the mechanical systems used in program G-2 should be used.

*Program Description:* A series of experiments should be designed to test refuse preparation and feeding systems. A pilot facility such as the one discussed in program H-2 should be utilized for this program. Funding will cover the survey testing of alternate systems and the development of schemes which show promise. The installation of various preparation and feed equipment to be utilized at the test site will also be funded by this program (assuming that program G-2 is not implemented). The effects of feed characteristics on pyrolysis products and rate will also be studied.

This is a two-year effort.

*Interdependencies:* A pilot unit such as the one developed in program H-2 is necessary prior to proceeding with this program. In addition, there will be other programs dependent upon the use of this pilot system. Therefore, the implementation of test programs will require careful scheduling.

*Priority:* High

*Man/Year Requirement:* four professionals, three technicians

*Cost:* $375,000 (including $100,000 in equipment)

### 5. R&D Program H-5 – *Study of Pyrolysis Product Control*

*Objective:* To determine the effects of air, steam, and/or hot flue gas injection on the pyrolysis rate and products.

*Discussion:* Because pyrolysis primarily involves the destructive distillation of materials in the absence of oxygen, the presence of air in the pyrolytic chamber will be minimized. In addition to the indirect energy supplied to the pyrolysis bed through the chamber walls, however, energy could also be supplied by the injection of steam, hot flue gases, or a limited quantity of air to promote combustion in the pyrolysis chamber. The effects of such techniques on the pyrolysis products and rates should therefore be evaluated.

It may be desirable, for example, to operate the system to yield entirely gaseous or both gaseous and liquid products. Char, when cleaned of metal and glass, may be an acceptable fuel, but it is more difficult to handle and may produce a particulate air pollution problem when burned. Data developed in program H-1 may be helpful in selecting operating conditions to optimize the fraction of refuse heat energy in the gas and/or liquid products.

*Program Description:* Experiments to determine the effects of varying quantities of steam, air, and hot flue gas injection on pyrolysis rates and resulting product mix should be designed. The experimental work could take place in the pilot scale facility discussed in program H-2.

This is a one-year effort.

*Interdependencies:* Data from program H-1 and the pilot facility are necessary.

*Priority:* High

*Man/Year Requirement:* two professionals, three technicians

*Cost:* $175,000

### 6. R&D Program H-6 – *Uses of Pyrolysis Products*

*Objective:* To evaluate the nature and uses of the gaseous, liquid, and char pyrolysis products.

*Discussion:* The economics of pyrolysis incineration will be affected by the possible by-product credits for the gaseous, liquid, and char residue material produced by the pyrolysis reaction. It is, therefore, important to define the nature of the product materials and explore potential uses. The product materials produced during pilot scale operation of a facility such as the one described in program H-2 will provide test samples.

*Program Description:* A pilot scale facility such as the one described in program H-2 will be required to generate the gaseous, liquid, and char pyrolysis products. Subsequent analysis of these materials will determine their composition and other significant characteristics. Depending upon the nature and properties of these materials, various alternatives can then be investigated for the economic utilization of such products. Consideration will be given to their value within the plant as a source of energy for the pyrolysis reaction and to uses external to the plant particularly in conventional combustion systems.

This is a one-year program.

*Interdependencies:* Same as interdependencies in program H-4.

*Priority:* High

*Man/Year Requirement:* one professional, two technicians

*Cost:* $100,000

### 7. R&D Program H-7 – *Evaluation of the Pyrolysis Air Pollution*

*Objective:* To determine the nature of air pollution from pyrolytic incineration.

*Discussion:* Because pyrolysis is a unique incinerator concept, the nature and the quantity of both gaseous and particulate pollutants may vary considerably from conventional incineration systems. A pilot test unit, such as the one described in program H-2, could be utilized to evaluate both the nature and quantity of pollutants emitted.

*Program Description:* A pilot unit, such as the one developed in program H-2, should be utilized to determine the nature and quantity of pyrolytic pollutant emissions. Emission data are necessary to indicate whether pollutant emissions from pyrolysis are uniquely different from conventional systems and, if so, whether new APC system designs or priorities (e.g., types that are more effective for gaseous pollutants, such as HCN or HCHO) may be required.

This is a one-year effort.

*Interdependencies:* The implementation of this program is dependent upon the availability of a pilot scale pyrolytic incinerator system such as the one discussed in program H-2. Data from most of the pyrolysis studies preceding it will be used.

*Priority:* High

*Man/Year Requirement:* one professional, two technicians

*Cost:* $100,000

### 8. R&D Program H-8 – *The Economics of Pyrolytic Incineration*

*Objective:* To carry out an economic evaluation of the pyrolysis incineration concept.

*Discussion:* Pending the successful completion of the preceding programs concerned with pyrolysis, an analysis of the economics of pyrolytic incineration should be performed. This analysis is necessary to determine the economic feasibility of those pyrolytic schemes which are technically sound. This study would eliminate undesirable process schemes, while indicating areas where more research and development are justified. Based on this cost analysis, competitive schemes could be identified and serve as a design basis for a future demonstration facility.

*Program Description:* This program involves consideration of capital investment and operating costs for pyrolytic incineration. The investment costs are dependent upon the design and selection of such components as refuse preparation and feeding systems as well as furnace design, associated process equipment, instrumentation, and controls. The operating costs will be primarily based on experience with the pilot unit and estimates of possible fuel sale net-backs.

This is a one-year effort.

*Interdependencies:* This study is highly dependent upon the results from programs H-1 to H-7 which will provide the necessary input data to this economic analysis. If this analysis shows that pyrolytic incineration is a competitive concept, incentive then exists for the design and construction of a full-scale demonstration pyrolysis incineration facility.

*Priority:* High

*Man/Year Requirement:* one professional

*Cost:* $50,000

### 9. R&D Program H-9 – *Design of a Full-Scale Pyrolytic System*

*Objective:* Design of a commercial-scale demonstration pyrolytic incineration facility.

*Discussion:* The design of such a demonstration facility is highly dependent upon the successful completion of the pilot-plant experimentation and the economic analysis of pyrolytic incineration as described in programs H-1 through H-8. The information obtained during these pilot test runs will serve as input to the design of the demonstration facility.

*Program Description:* The design of a pyrolytic prototype demonstration system will result in a series of drawings and blueprints from which such a system can be constructed. The design will include the refuse preparation system, feeding equipment, primary chamber, and associated process equipment. The design or selection of appropriate instrumentation and controls to monitor such a system properly and provide effective air pollution control devices will be included. The design will also consider residue handling facilities and a building enclosure including offices, locker rooms, and other related facilities.

This is a one-year program.

*Interdependencies:* As discussed above, the design of a pyrolytic prototype demonstration unit is highly dependent upon the successful completion of the pilot-scale programs.

*Priority:* High

*Man/Year Requirement:* four professionals, four draftsmen

*Cost:* $300,000

### 10. R&D Program H-10 – *Construction of a Full-Scale Pyrolysis System*

*Objective:* Construction of a commercial-scale pyrolysis incineration facility for demonstration.

*Discussion:* Pending the successful completion of the design of such a facility, construction can commence. As mentioned in connection with program G-7 (prototype fluid bed unit), it may be economical to locate this unit in proximity to the plant incinerator constructed under program F-2. Because of the possible use of the pyrolysis products by others, however, there may be commanding reasons to build the facility elsewhere.

*Program Description:* This program would include the preparation and evaluation of bids as well as the actual construction of the plant. Sufficient design and operational information could hopefully be obtained from this demonstration unit to commercialize the pyrolytic incineration concept.

This is an 18-month program.

*Interdependencies:* The construction of such a facility is directly dependent upon the successful completion of the design phase.

*Priority:* High

*Man/Year Requirement:* (included below)

*Cost:* $2,000,000 (total investment) ($1,500,000 if it adjoins pilot incinerator)

### 11. R&D Program H-11 – *Study of Full-Scale Pyrolysis*

***Objective:*** To carry out demonstration tests on the full-scale pyrolytic incineration system facility.

*Discussion:* The previously discussed development programs concerning the use of pyrolysis for refuse conversion require demonstration. This demonstration effort should verify, for example, plant operating economics, air pollution emissions, and product control and sales potential.

*Program Description:* Consistent with the design basis, operating variables will be adjusted to optimize plant performance. Process control systems and equipment performance will be evaluated and definitive capital and operating costs will be developed. If the sales of pyrolytic products is to be exploited, a study of combustion efficiency and other evaluations will be made to assess the value of these materials to the users.

This is an 18-month effort.

*Interdependencies:* These tests require use of the full-scale pyrolytic unit and may require adjacent fuel-burning facilities for evaluation of the utility of pyrolytic products as low-sulfur fuels.

*Priority:* High

*Man/Year Requirement:* eight professionals, ten technicians

*Cost:* **$75,000 ($550,000 if facility adjoins pilot incinerator facility)**

## I. ADVANCED CONCEPTS – SLAGGING INCINERATORS

The unique characteristic of slagging incineration systems is the production of a non-putrescible, non-combustible, and biologically sterile residue material. This inert residue leaves the furnace chamber as a liquid slag which subsequently solidifies. A granular material is obtained by quenching the slag in water, or a material more like crushed stone can be produced by slowly cooling the slag material in a pit to produce a frangible solid mass.

The character and nature of the air pollutants generated from slagging incinerators, in contrast to the desirable and unique qualities of the residue slag, are similar to those from conventional grate-type systems. In fact, the slagging concept may inherently yield more particulate than conventional facilities. Particulate loadings may be a factor of two higher than in contemporary plants. Also, nitrogen oxide emissions may be higher than in conventional incinerators due to greater furnace temperatures. The slagging incineration concept, however, may result in slightly lower combustible pollutant emissions than from conventional systems. Slagging systems, therefore, are more important in the reduction of solid waste than in the reduction of air pollutant emissions.

The research and development programs discussed in this study are oriented towards lower air pollution emissions from incinerators. Based on this criterion, the priorities of R&D expenditures directed towards the development of slagging incineration are not high. If, however, new data suggest air pollution reductions associated with slagging concepts, two basic R&D needs exist:

- The examination of the effects of refuse slag on refractory deterioration, and
- Determination of the effects of temperature and refuse content upon slag fluidity.

These needs will be discussed below. It should be recognized, however, that effort is now being expended in the areas mentioned and consideration of the progress, if any, should be given before implementing these proposed R&D programs.

### 1. R&D Program I-1 – *Effects of Refuse Slag*

*Objective:* To evaluate the effects of refuse slag on refractory deterioration.

*Discussion:* Refractory systems have been utilized in the metallurgical and pyroprocessing industries for several years under conditions where molten slag exists. The life of refractories utilized in the manufacture of such products as steel and glass vary considerably, but a life expectancy of five years is considered high. Very little experience, however, exists in evaluating the effects of continuous refuse slag flows on incinerator refractory. These effects should be determined; attention should also be given to the effects of refuse composition, fluxing aids and temperature on slagging properties as they affect refractories.

*Program Description:* A series of tests to determine the effects of refuse slag on refractory surfaces should be designed. These tests should reflect the variability of refuse composition as well as the effects of temperature on slagging properties. Experimentation could be carried out in a laboratory on a pilot-scale level prior to introducing it to a commercial facility. Various types of refractories should also be tested so that ultimately the effects of slagging on refractory can be determined for a range of refuse compositions, slagging temperatures, fluxing aid concentrations, and refractory types.

This is a one-year program.

*Interdependencies:* This program can be carried out independent of other R&D programs.

*Priority:* Low

*Man/Year Requirement:* one professional, two technicians

*Cost:* $100,000

### 2. R&D Program I-2 – *Slag Fluidity*

*Objective:* To determine the effects of temperature, fluxing aids, and refuse content upon the fluidity of refuse slag.

*Discussion:* To optimize the design of a slagging incineration system, the flow characteristics of refuse slag must be known for a variety of refuse compositions and slagging conditions. The design of slagging incinerators is highly dependent on this information. If the flow of refuse slag in a system is retarded and the slag solidifies or accumulates, furnace shutdown may be required at a loss in equipment availability. In addition, permanent damage to materials and process equipment may occur. Therefore, the need exists to understand and cope with the effects of refuse composition, temperature, and fluxing aids on the fluidity of refuse slag.

*Program Description:* A series of experiments to determine the effects of refuse composition, temperature, and other key parameters on the fluidity of refuse slag will be undertaken. The fluidity of the slag material should be examined as a function of such variables as furnace temperature, percent excess air, nature of the surfaces in contact with the slagging material, concentration of fluxing aids, and the composition of the refuse. Also, studies to determine whether the viscosity of the slag changes with time should be made. The results of the experiments should help to identify the appropriate temperature ranges and furnace geometries to permit the noninterrupted flow of slag and the minimum use of auxiliary fuel.

This is a one-year program.

*Interdependencies:* This program can be carried on independently of other R&D programs. However, there might be some mutual benefits in carrying out this program in conjunction with program I-1 as information obtained in either one of these programs might be useful to the other.

*Priority:* Low

*Man/Year Requirement:* one professional, two technicians

*Cost:* $100,000

## J. AIR POLLUTION CONTROL SYSTEMS

In classifying the air pollutants emanating from incinerator stacks, four basic types can be identified:

- combustible particulates,
- mineral particulates,
- combustible gases, and
- noncombustible gases.

Combustible Particulates

The effort to lessen the emission of combustible particulate can be approached from two different directions. One such direction is to improve the combustion efficiency of incineration systems. This can only be accomplished by mounting a design program based on a better understanding of the mechanisms of combustion in incineration and the effects of operating and design parameters on the combustion process. From the standpoint of overall cost effectiveness, this method of control appears to offer the greatest potential. Programs to provide this technology are discussed above.

A second approach is to improve the collection efficiency of existing APC devices used to control these pollutants. Section VII-B discusses the various air pollution control systems available and concludes that systems are presently available to adequately control particulates above 10 microns in diameter. In addition, bag filters and electrostatic precipitators both have the inherent capability of capturing particulate well below the 10-micron size range. Three basic concerns presently exist, however; viz.:

- The inability of fabric filters utilized in bag houses to cope with the tars and other organic solids which tend to clog and adhere to the material;
- The lack of reliable data on the particle size distribution of particulates below 10 microns, which is necessary as a basis for design; and
- The lack of data on comparative control efficiencies of existing APC devices.

The first problem can best be solved by improving the combustion process to eliminate the tars. The lack of information on particle sizes below 10 microns, however, is a valid concern, and effort to compile such data is certainly in order. Particle-size distribution in this size range should be determined as a function of particle composition, refuse composition, and the many key operating and design parameters characteristic of incineration systems. Program E-3 is directed to fulfilling this objective. However, little comparative data are available to evaluate the relative performance of APC systems. Program J-1 is designed to meet this need.

### Mineral Particulates

A similar, two-pronged effort should be made to reduce mineral particulates emissions. Programs F-7 and F-13 are concerned with the mechanisms of fine ash carryover from the refuse bed as well as the effects of operating them; design parameters on mineral particulate loading are also covered. Program J-1 is designed to identify APC system collection efficiency needs.

### Combustible Gaseous Pollutants

The principal combustible gaseous pollutants are carbon monoxide (CO) and the various individual organic pollutants classified as hydrocarbons (including polynuclear hydrocarbons). These pollutants result from the incomplete combustion of flue gases above the refuse bed. Several programs (F-4, F-6, F-10, and F-12) are concerned with understanding and improving the mechanisms of flue gas combustion.

We feel that limited priority should be given to programs concerned with the collection of combustible gaseous pollutants. The principal effort should be directed at improving combustion in the overfire volume as discussed in the above listed programs.

### Noncombustible Gaseous Pollutants

The principal noncombustible gaseous pollutants are the oxides of sulfur and nitrogen ($SO_2$ and $NO_X$), halogen acids, such as hydrogen chloride (HCl), and possibly trace quantities of volatile metal oxides, such as lead oxide (PbO). Limited available data suggest that incineration is a relatively minor contributor to the total $SO_2$ and $NO_X$ pollutant loads. In addition, the technology now under development for $NO_X$ and $SO_2$ control from other sources may be utilized for incinerators if warranted. Therefore, we feel that prime attention should be given to studies which quantify the nature and types of refuse materials contributing to the formation of noncombustible gaseous pollutants. By this means, incineration of these materials may possibly be avoided by controlling delivery to the incinerator system. In addition, studies such as programs F-9 and F-14 which examine the mechanisms of $NO_X$ formation in incinerators, address control of these pollutants by process variation to reduce their generation as the preferred alternative to special collection systems.

This discussion supports the philosophy that most programs should be directed at lowering pollution loading at the source, namely, within the incinerator. These needs are discussed in programs F-1 through F-14. In addition, several needs mentioned here are further discussed in section E. We feel that air pollution systems are presently at or near a level of development sufficient to meet stringent particulate air pollution codes. A primary concern, as discussed above, however, is the selection of appropriate devices. Program J-1 is directed towards comparing the relative efficiencies of existing units to enable a more cost-effective selection. Programs J-2 and J-3 are concerned with the more practical problems of handling and treating solid and liquid effluents from APC devices.

### 1. R&D Program J-1 – *APC System Evaluation*

*Objective:* Establishment of air pollution control efficiencies for alternative APC devices under controlled, but comparable conditions.

*Discussion:* Several contract and grant-supported studies which seek to evaluate the efficiency of APC devices are under way. In many cases, only particulate collection efficiency is evaluated. Some incinerator particulate emission data are available both prior to and following the APC device, and from this data some comparisons of efficiencies can be made. However, sampling techniques and operating procedures are often not presented in enough detail so that valid comparisons can be drawn between the reported efficiencies of different APC systems. The need, therefore, exists to better establish the efficiencies of alternative APC devices by evaluating their performance under controlled and comparable conditions. Of particular importance is identification of the fractional efficiency of APC systems for various particle sizes. This program should draw heavily on existing data.

Very little data exist on the levels of control for gaseous pollutants in wet APC systems. As discussed in Section VII-B, control effectiveness for these pollutants is related to the mass transfer characteristics of the APC device. Although a similar phenomenon controls mass transfer and particulate collection, the analogy is not one-to-one so that independent assessments of performance are required. The increasing emission rates forecast for hydrogen chloride (Chapter VI) places emphasis on the need for such data.

*Program Description:* The pilot-scale experimental incinerator to be implemented under program F-2 could be utilized effectively to carry out these experiments. Because the system will be designed with extensive controls and instrumentation, incineration operating variables can be regulated, together with the nature and properties of the refuse feed material, to maintain relatively constant furnace emissions characteristics. Alternative air pollution control devices could then be assembled and utilized with appropriate sampling and analysis techniques developed to yield the efficiency of operation. The results could then be examined and comparisons made between the efficiencies of alternative APC devices.

This is a one-year program.

*Interdependencies:* This R&D program is dependent on the implementation of programs F-1 and F-2 which recommend the design and construction of a test incineration facility.

*Priority:* High

*Man/Year Requirement:* two professionals, four technicians

*Cost:* $200,000*

### 2. R&D Program J-2 – *Fly Ash Handling*

*Objective:* Improvement of techniques for handling collected fly ash.

*Discussion:* One of the practical problems involved in the operation of municipal incineration facilities is the efficient handling of collected fly ash material. The light, dry, collected ash is susceptible to dusting, and its abrasive characteristics and corrosion potential have caused many problems in both wet and dry ash handling systems. Screw conveyors, for example, suffer from abrasion. Dust valves for cyclones have become plugged or have bypassed air, affecting APC effectiveness.

Improvement of fly ash handling equipment should be sought from the coal-burning construction materials (cement, rock processing), and mining industries, both of which have developed means to handle abrasive dusts. However, incinerator fly ash, because of its unique chemical and physical properties, presents somewhat different materials handling and corrosion problems.

*Program Description:* Techniques should be developed and tested for wet and dry handling of collected fly ash. This involves improved ash storage and valving systems and also techniques for transfer from storage hoppers to disposal vehicles or waste water lagoons.

This is a one-year program.

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**Note:* These costs do not include the costs of the air pollution control equipment to be tested. We are assuming here that these devices will not be purchased, but will be made available by the respective manufacturer.

*Interdependencies:* This program can be implemented independent of the other programs discussed.

*Priority:* Low

*Man/Year Requirement:* one professional, one technician

*Cost:* $75,000

### 3. R&D Program J-3 – *Treatment of Scrubber Water*

*Objective:* Improvement in the economics of scrubber water clarification and recycle.

*Discussion:* Wet air pollution control devices, such as high-energy scrubbers, absorb and entrain material which is often highly corrosive and abrasive. These materials can be neutralized and/or separated so that relatively clear water can be recycled to the APC device. This water treatment and clarification step is often costly, placing an economic burden on the operation of the plant utilizing such wet APC facilities. The alternative of once-through operation may also be prohibitively expensive, placing a substantial load on municipal sewage treatment facilities. There is need, therefore, to improve the water treatment processes to reduce the cost of air pollution control.

*Program Description:* Techniques should be developed and tested to improve the economics of water treatment and clarification. The technical and economic feasibility of new chemicals and/or different processing techniques should be examined. Also, consideration should be given to optimizing the quality of water to be recycled as a trade-off for the high costs of water treatment.

This is a one-year program.

*Interdependencies:* This program can be carried on independently of the other programs discussed.

*Priority:* Medium

*Man/Year Requirement:* one professional, two technicians

*Cost:* $100,000

## K. $5 MILLION RESEARCH PROGRAM

The programs comprising this $5 million research and development effort were selected primarily on the basis of their high priorities relative to the other programs presented in Chapter VIII. This high priority rating reflects their importance in meeting the overall objectives as they are discussed in the Introduction to this section. The $5 million program is focused, however, upon the development of improved incinerator technology based on the incorporation of well proven combustion principles in conventional incineration systems. In addition, expenditures were directed towards a more quantitative understanding of the nature and magnitude of air pollution from incineration as well as the exploration of the technical and economic merits of the pyrolysis concept.

Table VIII-1 is a milestone chart, which presents the programs selected to comprise a $5 million, 5-year research and development effort. Also illustrated in this table is the chronological sequence in which these programs are envisioned to be implemented. This chronology is based on the interdependencies as discussed in the program presentations.

The rate of expenditure during this 5-year research and development effort is graphically presented in Figure VIII-1. The vertical axis represents the cumulative funding costs with the horizontal axis indicating the time period over which these costs are incurred. The slope of this curve represents the rate of expenditure.

## L. $16 MILLION RESEARCH PROGRAM

The $16 million research and development effort is comprised of the total list of programs discussed above. They represent the total thrust of research and development needs over a 5-year period to meet adequately the goal of providing data and proven technology to reduce air pollution from incineration. They will include programs with priority ratings ranging from low to high. In each case, these priorities reflect the importance of that program in meeting the above goals. Successful completion of these programs does not constitute a solution to the overall solid waste disposal problem nor to all the problems of municipal incineration. These studies will, however, enable incineration system modification and construction which will assure a minimum of air pollution and a minimum of incurred capital and operating expenditures.

Table VIII-2 is a milestone chart which presents the programs comprising a $16 million, 5-year research and development effort. Also illustrated in this figure is the chronological sequence in which these programs are envisioned to be implemented. This chronology is based on the interdependencies as discussed in the program presentations.

TABLE VIII-1

## MILESTONE CHART FOR 5-YEAR, $5-MILLION RESEARCH A

| | R&D Programs | Cost ($000) | FY-#1 June | FY-#1 Dec. | FY-#2 June | FY-#2 Dec. |
|---|---|---|---|---|---|---|
| D-6 | Forecast of Disposal Trends | $ 70 | X - - - - | - - - - - - | - - - X | |
| E-1 | Test Method Development | 150 | X - - - - | - - - - - - | - - - X | |
| E-2 | Incinerator Testing | 600 | | | | X - - - - - - |
| F-1 | Pilot Incinerator Design | 150 | X - - - - | - - - - - - | - - - - - - | - - - X |
| F-2 | Pilot Facility Construction | 1,250 | | | X - - - - | - - - - - - |
| F-3 | Fundamental Refuse Combustion Study | 150 | X - - - - | - - - - - - | - - - - - - | - - - - - - |
| F-4 | Fundamental Mixing Study | 200 | X - - - - | - - - - - - | - - - - - - | - - - - - - |
| F-5 | Combustion Study, Pilot-Scale | 150 | | | | |
| F-6 | Mixing Study, Pilot-Scale | 150 | | | | |
| F-7 | Particulate Study-Pilot-Scale | 75 | | | | |
| F-12 | Overfire Combustion Study, Full-Scale | 450 | | | | |
| G-5 | Fluid Bed Economics | 50 | X - - - - | - - - - - - | - - - X | |
| H-1 | Basic Pyrolytic Studies | 150 | X - - - - | - - - - - - | - - - - - - | - - - - - - |
| H-2 | Pilot Pyrolytic System Design | 125 | | X - - - - | - - - - - - | - - - X |
| H-3 | Pyrolytic Pilot Unit Construction | 475 | | | X - - - - | - - - - - - |
| H-4 | Pyrolytic Feed Preparation-Pilot-Scale | 375 | | | | |
| H-6 | Pyrolytic Product Uses | 100 | | | | |
| H-7 | Pyrolytic Air Pollution Evaluation | 100 | | | | |
| H-8 | Economics of Pyrolysis Incineration | 50 | | | | |
| J-1 | APC System Evaluation | 200 | | | | |

TABLE VIII-1

R 5-YEAR, $5-MILLION RESEARCH AND DEVELOPMENT PROGRAM

|  | FY-=2 June | Dec. | FY-=3 June | Dec. | FY-=4 June | Dec. | FY-=5 June | Dec. | June |
|---|---|---|---|---|---|---|---|---|---|
| ···· | X |  |  |  |  |  |  |  |  |
| ···· | X |  |  |  |  |  |  |  |  |
|  |  | X | ···· | ···· | ···· | X |  |  |  |
| ···· | ···· | X |  |  |  |  |  |  |  |
|  | X | ···· | ···· | X |  |  |  |  |  |
| ···· | ···· | ···· | X |  |  |  |  |  |  |
| ···· | ···· | ···· | X |  |  |  |  |  |  |
|  |  |  | X | ···· | X |  |  |  |  |
|  |  |  | X | ···· | X |  |  |  |  |
|  |  |  | X | ···· | X |  |  |  |  |
|  |  |  |  |  | X | ···· | ···· | ···· | X |
|  |  |  |  |  |  |  |  |  |  |
| ···· | X |  |  |  |  |  |  |  |  |
| ···· | ···· | ···· | X |  |  |  |  |  |  |
| ···· | ···· | X |  |  |  |  |  |  |  |
|  | X | ···· | X |  |  |  |  |  |  |
|  |  |  | X | ···· | ···· | ···· | X |  |  |
|  |  |  |  | X | ···· | X |  |  |  |
|  |  |  |  | X | ···· | X |  |  |  |
|  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  | X | ···· | X |  |  |
|  |  |  |  |  |  |  |  |  |  |
|  |  |  |  | X | ···· | X |  |  |  |

## TABLE VIII-1

## MILESTONE CHART FOR 5-YEAR, $5-MILLION RESEAR

| | R&D Programs | Cost ($000) | FY-#1 June | FY-#1 Dec. | FY-#2 June | FY-#2 Dec. |
|---|---|---|---|---|---|---|
| D-6 | Forecast of Disposal Trends | $ 70 | X------ | ------ | X | |
| E-1 | Test Method Development | 150 | X------ | ------ | X | |
| E-2 | Incinerator Testing | 600 | | | | X------ |
| F-1 | Pilot Incinerator Design | 150 | X------ | ------ | ------ | X |
| F-2 | Pilot Facility Construction | 1,250 | | | X------ | ------ |
| F-3 | Fundamental Refuse Combustion Study | 150 | X------ | ------ | ------ | ------ |
| F-4 | Fundamental Mixing Study | 200 | X------ | ------ | ------ | ------ |
| F-5 | Combustion Study, Pilot-Scale | 150 | | | | |
| F-6 | Mixing Study, Pilot-Scale | 150 | | | | |
| F-7 | Particulate Study-Pilot-Scale | 75 | | | | |
| F-12 | Overfire Combustion Study, Full-Scale | 450 | | | | |
| G-5 | Fluid Bed Economics | 50 | X------ | ------ | X | |
| H-1 | Basic Pyrolytic Studies | 150 | X------ | ------ | ------ | ------ |
| H-2 | Pilot Pyrolytic System Design | 125 | | X------ | ------ | X |
| H-3 | Pyrolytic Pilot Unit Construction | 475 | | | X------ | ------ |
| H-4 | Pyrolytic Feed Preparation-Pilot-Scale | 375 | | | | |
| H-6 | Pyrolytic Product Uses | 100 | | | | |
| H-7 | Pyrolytic Air Pollution Evaluation | 100 | | | | |
| H-8 | Economics of Pyrolysis Incineration | 50 | | | | |
| J-1 | APC System Evaluation | 200 | | | | |

## TABLE VIII-1

## OR 5-YEAR, $5-MILLION RESEARCH AND DEVELOPMENT PROGRAM

|  | FY-#2 |  | FY-#3 |  | FY-#4 |  | FY-#5 |  |  |
|---|---|---|---|---|---|---|---|---|---|
| c. | June | Dec. | June | Dec. | June | Dec. | June | Dec. | June |
| - - - | X |  |  |  |  |  |  |  |  |
| - - - | X |  |  |  |  |  |  |  |  |
|  |  | X | - - - | - - - | - - - | X |  |  |  |
| - - - | - - - | X |  |  |  |  |  |  |  |
|  | X | - - - | - - - | X |  |  |  |  |  |
| - - - | - - - | - - - | X |  |  |  |  |  |  |
| - - - | - - - | - - - | X |  |  |  |  |  |  |
|  |  |  | X | - - - | X |  |  |  |  |
|  |  |  | X | - - - | X |  |  |  |  |
|  |  |  | X | - - - | X |  |  |  |  |
|  |  |  |  |  | X | - - - | - - - | - - - | X |
| - - - | X |  |  |  |  |  |  |  |  |
| - - - | - - - | - - - | X |  |  |  |  |  |  |
| X | - - - | X |  |  |  |  |  |  |  |
|  | X | - - - | X |  |  |  |  |  |  |
|  |  |  | X | - - - | - - - | - - - | X |  |  |
|  |  |  |  | X | - - - | X |  |  |  |
|  |  |  |  | X | - - - | X |  |  |  |
|  |  |  |  |  | X | - - - | X |  |  |
|  |  |  |  | X | - - - | X |  |  |  |

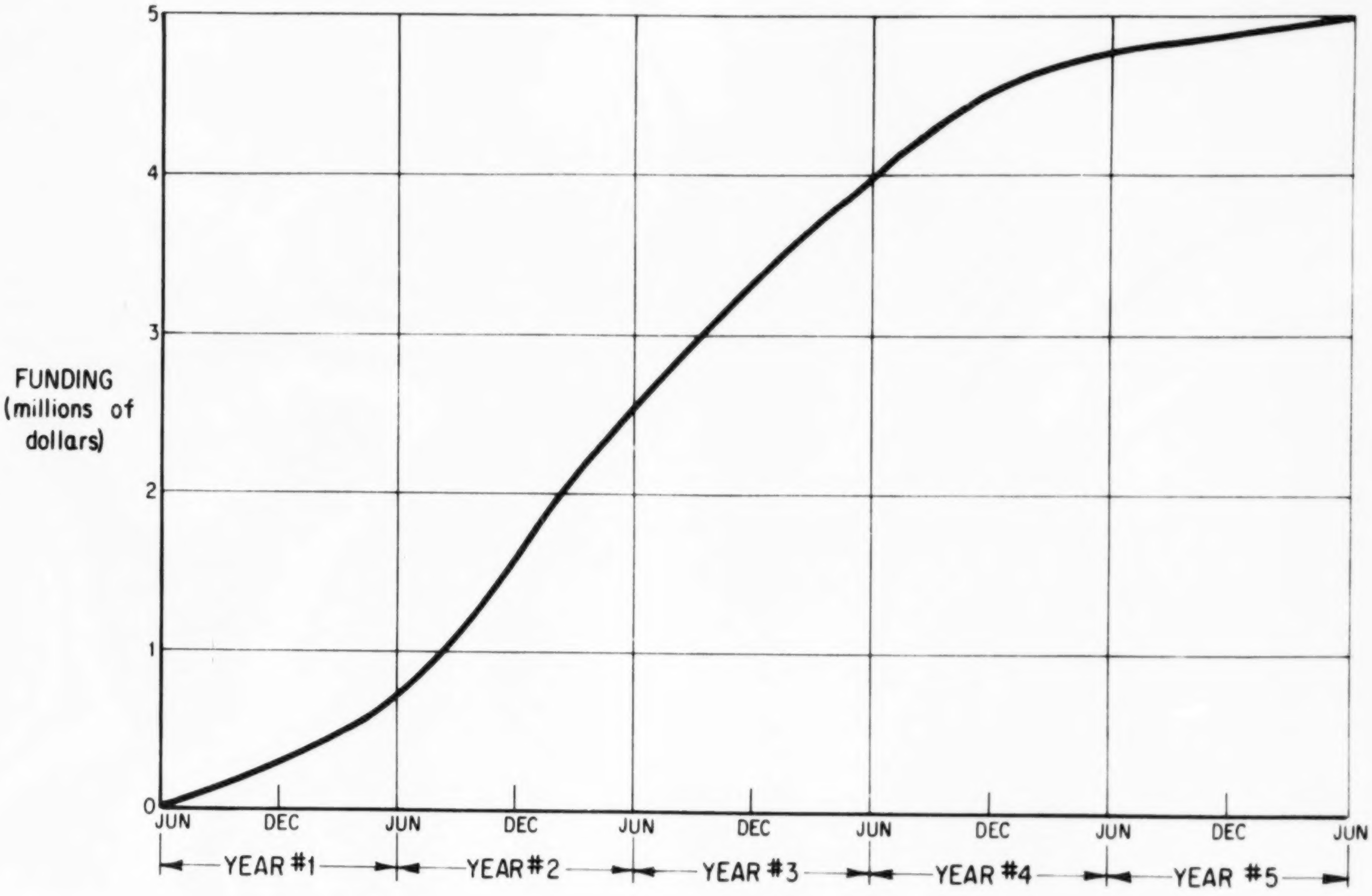

FIGURE VIII-1 FIVE YEAR – 5 MILLION DOLLAR RESEARCH AND DEVELOPMENT PROGRAM – RATE OF EXPENDITURE GRAPH

TABLE VIII-2

## MILESTONE CHART FOR $16 MILLION RESEARC

|  | R&D Programs | Cost ($000) | FY-#1 |  | FY-#2 |  |
|---|---|---|---|---|---|---|
|  |  |  | June | Dec. | June | Dec. |
| D-1 | Mobile Laboratory | $ 350 | X | - - - | - - - | X |
| D-2 | Refuse Properties | 750 |  |  |  | X - - |
| D-3 | Refuse Composition Forecasts | 50 |  |  |  |  |
| D-4 | Gaseous Pollutant Emission Forecasts | 50 |  |  | X | - - - |
| D-5 | Refuse Heat Content Control | 100 | X | - - - | X |  |
| D-6 | Forecast of Disposal Trends | 70 | X | - - - | X |  |
| E-1 | Test Method Development | 150 | X | - - - | X |  |
| E-2 | Incinerator Testing | 600 |  |  | X | - - - |
| E-3 | Particulate Size Distributions | 200 |  |  | X | - - - |
| E-4 | Total Incinerator Pollution Forecasts | 50 |  | X | - - - | X |
| F-1 | Pilot Incinerator Design | 150 | X | - - - | - - - | X |
| F-2 | Pilot Facility Construction | 1,250 |  | X | - - - | - - - |
| F-3 | Fundamental Refuse Combustion Study | 150 | X | - - - | - - - | - - - |
| F-4 | Fundamental Mixing Study | 200 | X | - - - | - - - | - - - |
| F-5 | Combustion Study, Pilot-Scale | 150 |  |  |  |  |
| F-6 | Mixing Study, Pilot-Scale | $ 150 |  |  |  |  |
| F-7 | Particulate Study - Pilot-Scale | 75 |  |  |  |  |
| F-8 | Suspension Burning Studies, Pilot-Scale | 225 |  |  |  |  |
| F-9 | $NO_x$ Studies, Pilot-Scale | 75 |  |  |  |  |
| F-10 | Combustible Particulate Studies | 150 |  |  |  |  |
| F-11 | Bed Combustion Study, Full-Scale | 450 |  |  |  |  |
| F-12 | Overfire Combustion Study, Full-Scale | 450 |  |  |  |  |
| F-13 | Particulate Study, Full-Scale | 250 |  |  |  |  |
| F-14 | $NO_x$ Study, Full-Scale | 100 |  |  |  |  |

## H AND DEVELOPMENT PROGRAM

| | FY-=3 | | FY-=4 | | FY-=5 | | |
|---|---|---|---|---|---|---|---|
| | June | Dec. | June | Dec. | June | Dec. | June |
| ········· | ········· | ········· | ········· | X | | | |
| | | X········· | ········· | X | | | |
| ········· | X | | | | | | |
| ········· | ········· | ········· | X | | | | |
| ········· | ········· | ········· | X | | | | |
| ········· | X | | | | | | |
| ········· | X | | | | | | |
| ········· | X | | | | | | |
| | X········· | ········· | X | | | | |
| | X········· | ········· | X | | | | |
| | X········· | ········· | X | | | | |
| | X········· | ········· | X | | | | |
| | X········· | ········· | X | | | | |
| | | X········· | ········· | X | | | |
| | | | X········· | ········· | ········· | ········· | X |
| | | | X········· | ········· | ········· | ········· | X |
| | | | X········· | ········· | ········· | ········· | X |
| | | | X········· | ········· | ········· | ········· | X |

TABLE VIII-2 (Continu

|  | R&D Programs | Cost ($000) | FY-=1 June | FY-=1 Dec. | FY-=2 June | FY-=2 Dec. |
|---|---|---|---|---|---|---|
| G-1 | Pilot Fluid Bed Construction | $ 225 | X········ | ········ | ········ | X |
| G-2 | Fluid Bed Feeding Concepts | 550 |  |  | X········ | ········ |
| G-3 | Fluid Bed Additive Study | 100 |  |  |  | X····· |
| G-4 | Fluid Bed Combustion Study | 100 |  |  |  | X····· |
| G-5 | Fluid Bed Economics | 50 | X········ | ········ | X |  |
| G-6 | Prototype Fluid Bed Design | 250 |  |  |  |  |
| G-7 | Prototype Fluid Bed Construction | 2,000 |  |  |  |  |
| G-8 | Prototype Fluid Bed Study | 550 |  |  |  |  |
| H-1 | Basic pyrolytic Studies | 150 | X········ | ········ | ········ | ········ |
| H-2 | Pilot Pyrolytic System Design | 125 | X········ | ········ | X |  |
| H-3 | Pyrolytic Pilot Unit Construction | 475 |  | X········ | ········ | X |
| H-4 | Pyrolytic Feed Preparation, Pilot-Scale | 375 |  |  | X········ | ········ |
| H-5 | Pyrolysis Product Control Study | 175 |  |  |  |  |
| H-6 | Pyrolysis Product Uses | 100 |  |  |  |  |
| H-7 | Pyrolysis Air Pollution Evaluation | 100 |  |  |  |  |
| H-8 | Economics of Pyrolysis Incineration | 50 |  | X········ | ········ | X |
| H-9 | Full-Scale Pyrolysis System Design | 300 |  |  |  |  |
| H-10 | Full-Scale Pyrolysis System Construction | 2,000 |  |  |  |  |
| H-11 | Full-Scale Pyrolysis Study | 750 |  |  |  |  |
| I-1 | Refuse Slag Effects. | 100 | X········ | ········ | X |  |
| I-2 | Slag Fluidity | 100 | X········ | ········ | X |  |
| J-1 | APC System Evaluation | 200 |  |  |  |  |
| J-2 | Fly Ash Handling | 75 |  |  |  |  |
| J-3 | Scrubber Water Treatment | 100 |  |  |  |  |

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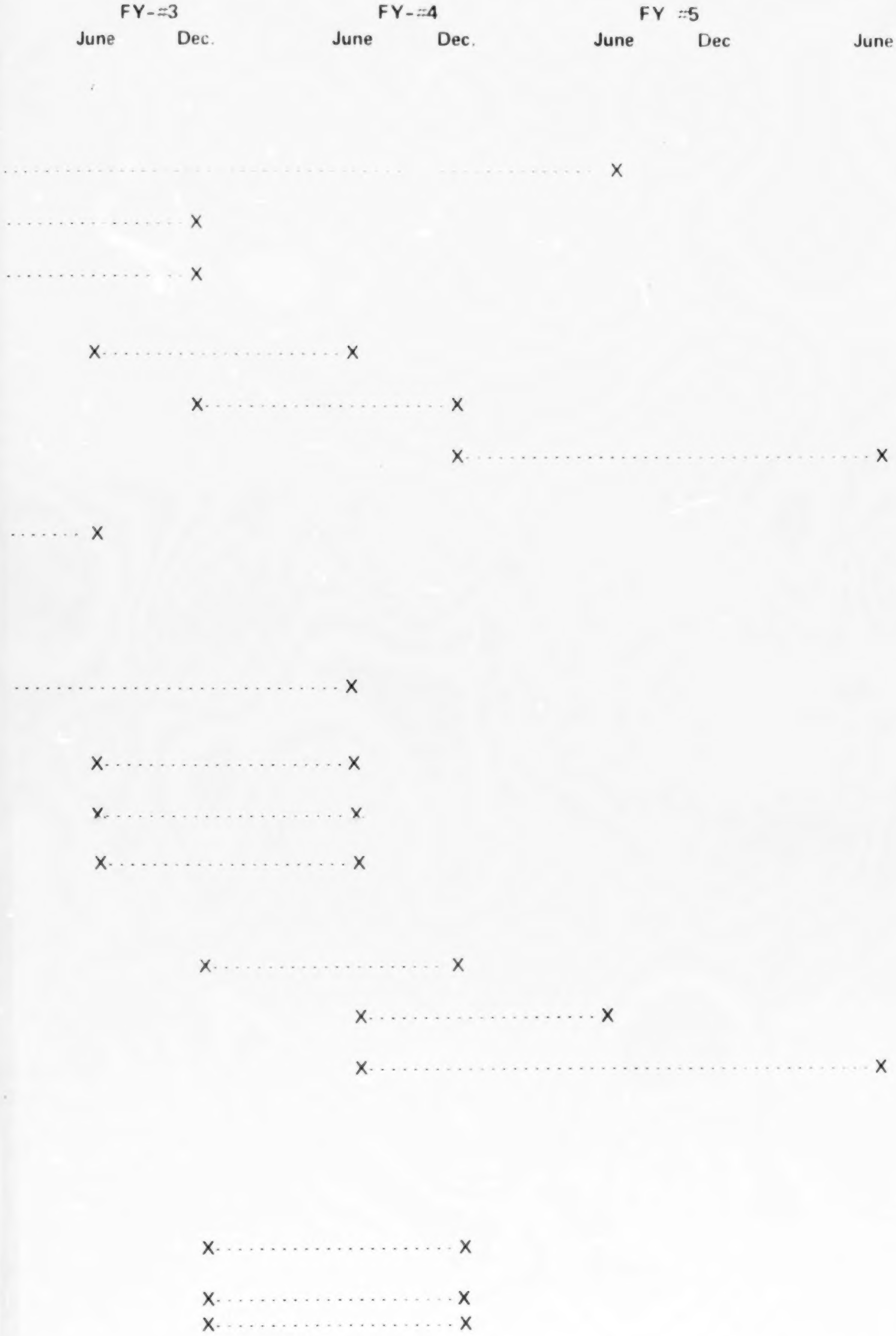

The rate of expenditure during this 5-year research and development effort is graphically presented in Figure VIII-2. The vertical axis represents the cumulative funding costs with the horizontal axis indicating the time period over which these costs are incurred. The slope of this curve represents the rate of expenditure.

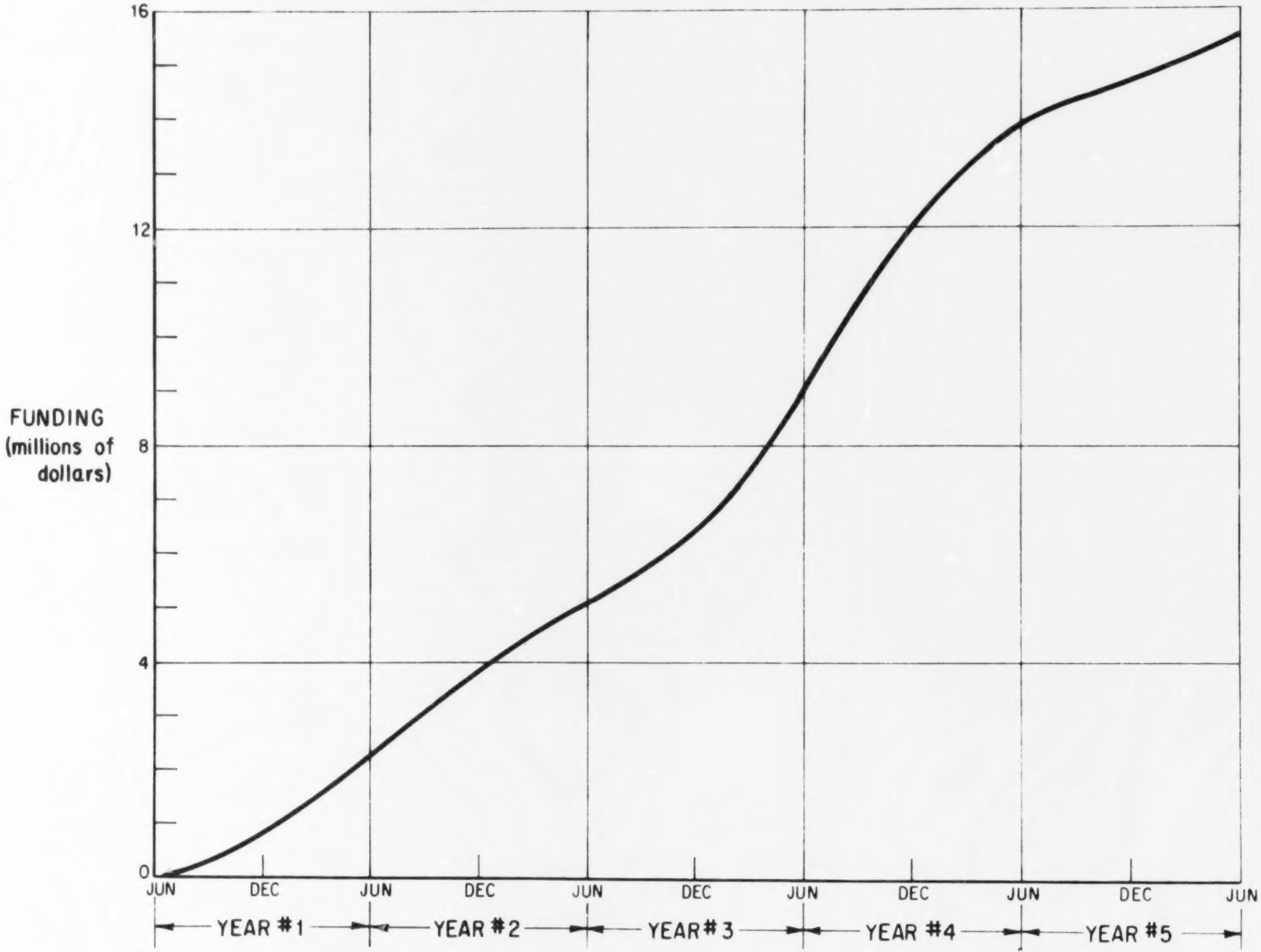

FIGURE VIII-2 FIVE YEAR – $16 MILLION RESEARCH PLAN – RATE OF EXPENDITURE GRAPH

CAMBRIDGE,
MASSACHUSETTS

CHICAGO
NEW YORK
SAN FRANCISCO
SANTA MONICA
WASHINGTON
ATHENS
BRUSSELS
CARACAS
LONDON
MEXICO CITY
PARIS
RIO DE JANEIRO
TORONTO
ZURICH

RECEIVED
JUL 8 1970
INPUT SECTION
CLEARINGHOUSE